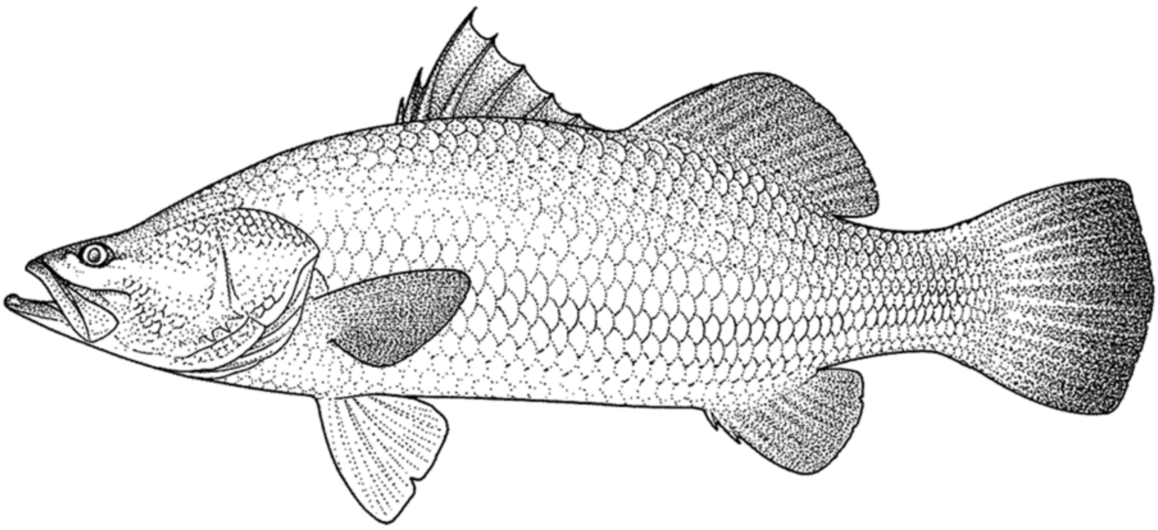
Assessment of the barramundi (*Lates calcarifer*) fishery in the Southern Gulf of Carpentaria, Queensland, Australia.

Date: August 2017



piSeas

Queensland Government

This publication has been compiled by Alexander Campbell of piSeas Pty Ltd and Julie Robins and Michael O'Neill of Agri-Science Queensland, Department of Agriculture and Fisheries.

Table of contents

Table of tables

Table of figures

Executive Summary

Wild-capture barramundi (*Lates calcarifer*) forms the basis of important commercial, recreational and customary Indigenous fisheries in Queensland, with an estimated harvest of about 700 tonnes in 2015 (Saunders *et al.* 2016). For stock status assessment, barramundi in Queensland are considered to consist of seven genetically distinct populations. Within the Gulf of Carpentaria (GoC), there are two genetic stocks split at around 13° S - a Northern Gulf of Carpentaria stock and a Southern Gulf of Carpentaria stock. The Gulf of Carpentaria Inshore Fin Fish Fishery harvests barramundi from both these stocks, but the current assessment focuses on the Southern Gulf of Carpentaria (Southern GoC) barramundi stock, which produces, on average, greater than 50% of the annual commercial harvest of barramundi in Queensland and was listed as transitional-depleting in the 2016 Status of Australian Fish Stocks report (Saunders *et al*. 2016).

Commercial net fishing for barramundi expanded rapidly in the Gulf of Carpentaria in the 1970s, with fishing effort peaking around 1977 before declining steadily until around 1985. The fishing pressure applied during this time was believed to have had a significant impact on the barramundi stocks in the Gulf of Carpentaria (Quinn, 1984), and was the impetus for management intervention. Restricted access was introduced for the commercial Gulf of Carpentaria net fishery in 1981 when 191 endorsements were issued. Additionally, a closed spawning season was introduced, with no inshore commercial net fishing or recreational harvest permitted between approximately October and February. A recreational possession limit for barramundi was also introduced. Further management intervention has occurred with the introduction of a mesh size limit in 1989, then a specified maximum legal size limit in 1992. Access to the commercial fishery (i.e., the Gulf of Carpentaria Inshore Fin Fish Fishery) has been further restricted over time with reductions in the number of N3 symbols, from 109 in 1998 to 85 in 2015.

To assess the status of the stock, a traditional age-structured population model with an annual time step was developed for the Southern GoC stock. The model was driven by commercial fishing effort, and fitted to commercial catch and observed barramundi age-frequencies. It considered male and female contributions to reproduction separately, by incorporating age-based sex-ratio information, and significant attention was paid to reconstructing, as accurately as possible, the history of fishing effort back to 1954.

Model sensitivity to the following aspects was explored: barramundi reproductive rate; barramundi growth rate; net selectivity-at-fish-length and -age; importance of the barramundi age-frequency data; natural mortality; duration of the catch history used in the model fitting process; and increases in catchability of fish over time. This resulted in 16 alternative scenarios, summarised in Table 4. Five scenarios had acceptable fits to the data and were considered to represent plausible alternatives. Detailed results for these five scenarios are reported upon here.

The primary stock status indicator considered was the Egg Production Ratio (EPR). This is the ratio of the egg production of the stock over the last seven years of the time series (i.e., average over the period 2009 to 2015) compared to egg production prior to the commencement of fishing (i.e., 1954). A seven-year average was chosen to construct an indicator that was robust to the presence of strong environmental variation, taking into account the typical generation time of the species. Estimates for EPR for the five alternative scenarios were 0.33, 0.33, 0.34, 0.41 and 0.41 (confidence intervals ranged from 0.22 to 0.60). These values are below 0.48 EP_0/B_0 (egg production / biomass prior to fishing), which is the proxy level in Commonwealth managed fisheries for the biomass necessary to achieve maximum economic yield (itself often used as a proxy for robust biomass levels). However, the estimated values are above 0.20 EP_0, which is a common proxy for the biomass below which the risk to a stock is regarded as unacceptably high (the so-called B_{lim}). For more information on these proxies see for example the Australian Government (2007), Sainsbury (2008), Sloan *et al*. (2014) and Stewardson *et al*. (2016).

In addition to EPR, which tells us what is happening right now (or as close to now as possible, which in this case is over the last seven years), we also considered "equilibrium" indicators. These are quantities that only make sense in the long term. Equilibrium indicators are more ambitious in the sense that, in principle at least, they indicate the level of fishing and population size that would maximise yield in *this particular* fishery (as opposed to measuring against a rule of thumb based on a generic fishery). However, equilibrium indicators are also more prone to be misleading if the data provide insufficient information or if the model is mis-specified.

Three equilibrium indicators were calculated: Maximum Sustainable Yield (MSY), which was quantified by simulating the fishery into the future with parameters fixed at their estimated values and optimising yield over all possible fishing mortality rates; Egg Production at MSY (EPR_{MSY}) which is the ratio of egg production of the stock over the last seven years of the time series (average over 2009 to 2015) to egg production at MSY; and Fishing Ratio (FR) which is the ratio of current fishing mortality (in 2015) to the fishing mortality at MSY. Estimates for EPR_{MSY} were all considerably greater than one, ranging from 1.75 to 2.75 across the five scenarios. Estimates for fishing ratio (FR) were all considerably less than one, ranging from 0.41 to 0.59. These values suggest that the stock is not recruitment overfished (i.e., EPR_{MSY} >1.0), and also that the stock is not currently experiencing recruitment overfishing (i.e., FR <1.0). Estimates for MSY ranged between 599 and 715 tonnes.

Thus, the EPR indicator and the equilibrium indicators tell different stories. We consider that EPR is a more appropriate indicator of stock status in the Southern GoC barramundi stock than any of the equilibrium-based indicators (i.e., MSY, EPR_{MSY} or FR) because the data were insufficient to simultaneously estimate both natural mortality and reproductive strength, and because of the strong environmentally driven variation in recruitment and catch - in other words, the barramundi stocks in the GoC are rarely in an equilibrium state.

According to model estimates for EPR, the Southern GoC barramundi stock is currently above critical biomass levels, but below target levels. Model results also suggest that the stock was indeed seriously depleted following the high fishing effort in the 1970s and early 1980s. Model results also suggest that the various management arrangements introduced for barramundi since 1980 in the Gulf of Carpentaria have supported the stock in recovering from these depleted levels, but have not necessarily brought the stock back to optimal levels from an ecological, economic or social perspective. Recent trends (over the last seven years) in spawning ratios show no clear improvements. The cause of this is uncertain: it may indicate current fishing pressure is limiting stock recovery toward a target level, or it may be a consequence of major and widespread drought in catchments that contribute to the Southern GoC stock. Driving a population model with environmental signals would help to distinguish between these possible causes.

The fish length, age, and gender data collected for barramundi as part of the Long Term Monitoring Program by Fisheries Queensland were critically important in developing stock-specific curves for growth-at-age, selectivity-at-age, male maturity-at-age, and female proportion-at-age. The data were also essential for deriving the parameter estimates and model fits because of their role in quantifying mortality and general population dynamics. The importance of a long, continuous time-series of stock-specific length- and age-structure, and gender data cannot be over emphasised, especially for a species like barramundi in the GoC which has large variation in both recruitment and catch.

Key Recommendations:

- Continue sampling length, age and gender information for barramundi, especially in the Southern GoC, sufficient to capture variability within this spatially diverse stock.
- Improve CFISH logbook data (quality and detail). Details that would support effort standardisation should include mesh size(s), net length, placement, location fished and other quantifiers of effort, for example, hours fished per day, number of retrievals, number of sets and net soak time.
- Validate CFISH logbook data.
- Although not a major issue for the Southern GoC barramundi stock, all stocking events should be quantitatively recorded by Fisheries Queensland in a central database, including as a minimum: date, number of fish stocked, average length, and location of release. The population dynamics of barramundi stocks on the Queensland east coast are potentially confounded by stocked fingerlings, and without such data, quantitative assessment of other Queensland barramundi stocks (especially the north-east coast) will be compromised.
- Growth rates play an important role in stock assessment, and variation in growth rates can potentially lead to a different outcome. Data that assist with estimating spatial and temporal variation in fish growth should be obtained.
- The inclusion of environmental drivers such as river flow in stock assessments should continue to be a goal for barramundi, with ongoing research and data collection to support this.

Acknowledgements

We thank the following people for their contributions:

Olivia Whybird (Fisheries Queensland Long Term Monitoring Program) for the supply of length, age and gender data and corresponding R code to transform the raw data into a form useable by the model.

Nadia Engstrom and Anna Garland (Fisheries Queensland) for supply of the commercial catch and effort data from CFISH.

David Mayer (Agri-Science Queensland) for analysis of the proportion of female-at-age.

George Leigh (Agri-Science Queensland) for helpful advice on finding alternative solutions to scenarios with high steepness.

Past and present DPI/DAF employees whose opinions, reports and data were the basis on which historical effort and catch were reconstructed, notably Peter Tanner, Lew Williams, Ross Quinn, Neil Gribble, Rod Garrett, John Russell and Mal Pearce.

Warwick Nash (Agri-Science Queensland) for comment and feedback.

The stock assessment of barramundi was managed collaboratively through a project committee. The following project committee staff, in addition to the authors, assisted throughout the project: Olivia Whybird, Michael Mikitis, Peter Kind, Malcolm Pearce and Tony Ham.

We also thank the entire Fisheries Queensland Long Term Monitoring Program team, past and present, and the fishers and processors who assisted them, in obtaining and processing the length, age and other biological data which are so critical to this stock assessment.

Introduction

Wild-capture barramundi (*Lates calcarifer*) forms the basis of important commercial, recreational and customary Indigenous fisheries in Queensland, with an estimated combined harvest in the order of 700 tonnes in 2015 (Saunders *et al*. 2016).

The development of quantitative models for barramundi (Gribble 2004; Campbell *et al.* 2008; Hall *et al.* 2008; Tanimoto *et al.* 2012) has been challenged by the complex nature of the barramundi life-cycle (Dunstan 1959; Russell 2014), data quality issues (Campbell *et al.* 2008), and the influence of environmental factors on key biological processes and the fishery (Dunstan 1959; Davis 1982; Staunton-Smith *et al.* 2004; Robins *et al.* 2006). A further complication includes the effects of stocking barramundi fingerlings upstream that eventually contribute to the wild-caught fishery (Rimmer and Russell 1998; Wesche *et al.* 2013).

Campbell *et al*. (2008) highlighted the need for improved age, selectivity and logbook data for the barramundi fishery in Queensland. This need has been addressed to some degree with the routine collection of fish age, length and gender data by the Queensland Fisheries Long Term Monitoring Program (LTMP) which now has an extended time series of data (Fisheries Queensland 2010).

The current assessment focuses on the Southern Gulf of Carpentaria barramundi stock, which produces, on average, greater than 50% of the barramundi harvest in Queensland and was listed as transitional-depleting in the 2016 Status of Australian Fish Stocks report (Saunders *et al*. 2016).

Background

Biology

Barramundi have a complex and spatially variable life history. For a detailed review see Russell (2014). From a stock assessment perspective, key aspects of the life history of barramundi in Queensland are:

- Longevity: barramundi are relatively long lived, with specimens of 20 years old recorded from the Gulf of Carpentaria and 35 years old recorded from the Fitzroy River, Queensland east coast.
- Protandry: most barramundi mature first as males (at two to five years), with females derived from sexually mature males at five to seven years of age (Moore 1979; Davis 1984).
- Seasonal spawning: barramundi spawn during spring and summer, with the timing and duration of the spawning dependent on water temperature, and lunar and tidal cycles.
- Non-obligatory catadromy, that is, movement between salt and freshwater: although spawned in high salinity water, barramundi can use numerous habitats, from fully marine to fully freshwater, during their life cycle. Supra-littoral coastal swamps act as nursery areas for juvenile barramundi. Where access permits, a variable proportion of juvenile barramundi will swim upstream to freshwater habitats, while the remainder stay in estuarine habitats. The duration and locality (i.e., distance upstream) of freshwater residency is variable between individuals, rivers and years (Halliday *et al*. 2012).
- Environmental influences: The influence of rainfall on barramundi catches has been noted for several decades (Dunstan 1959; Williams 2002; Gribble *et al*. 2005). Rainfall and seasonal flooding of rivers affect the relative recruitment of young-of-the-year barramundi (Staunton-Smith *et al.* 2004; Halliday *et al.* 2012). River-flow also affects barramundi growth rates (Sawynok 1998;

Robins *et al.* 2006). Additionally, seasonal flooding allows the downstream movement of freshwater residents, thereby influencing the overall fish age- and length-structure of harvested barramundi, as well as increasing the catchability of fish and the absolute tonnage of the commercial catch.

Stock Structure

Stock structure analysis has identified six (Keenan 1994), seven (Shaklee *et al.* 1993) or eight (Jerry *et al.* 2013) genetically distinct barramundi populations in Queensland. The current report adopts the same stock structure for barramundi as Fisheries Queensland when reporting on national fish stock sustainability (Saunders *et al*. 2016). The current assessment focuses on the Southern Gulf of Carpentaria (Southern GoC) stock, which extends from 13° S (~ Watson River) on Western Cape York to the Queensland/Northern Territory border at ~138° E (**Figure 1**).

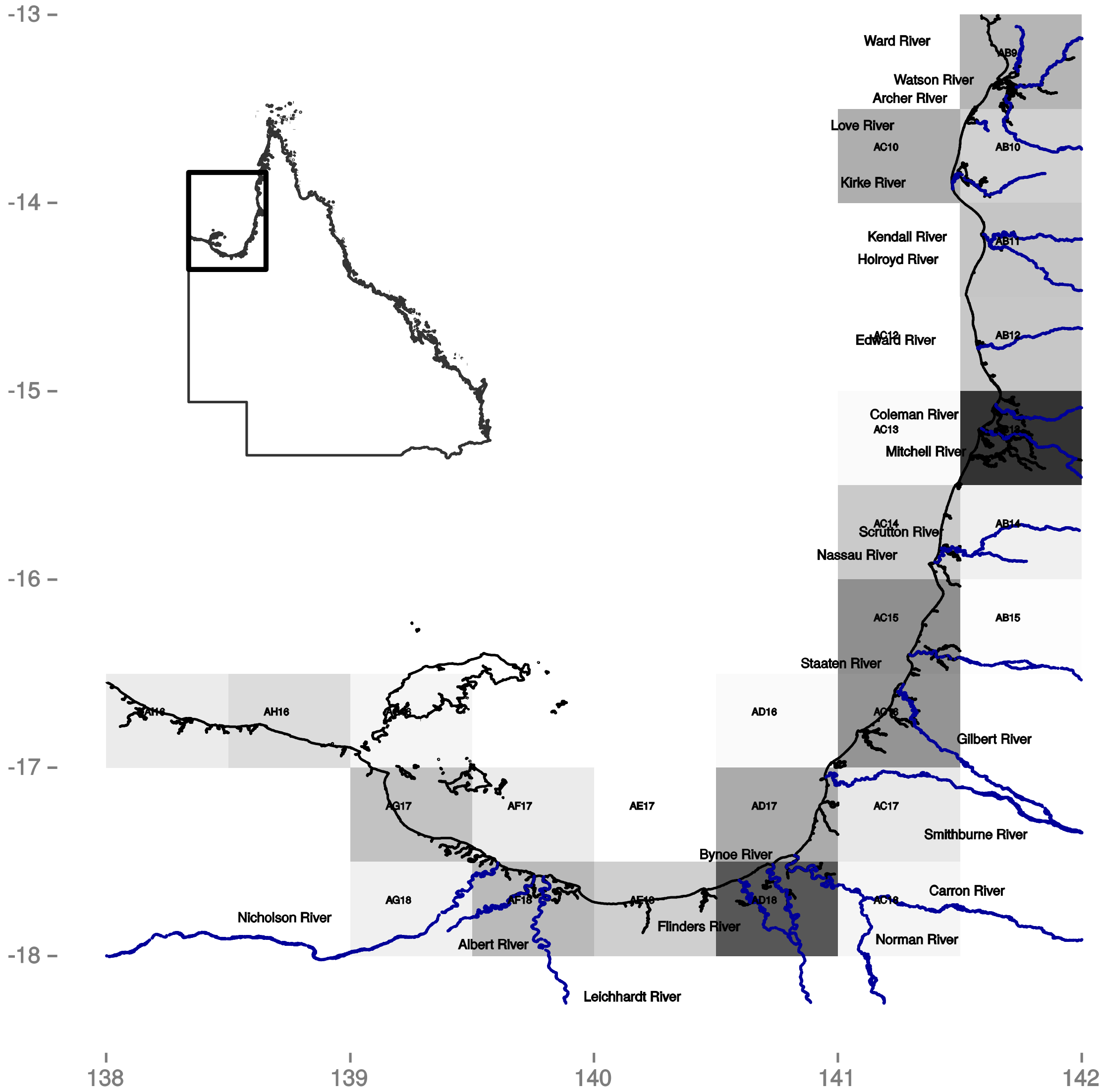


Figure 1 - Spatial extent of the Southern Gulf of Carpentaria barramundi stock showing major rivers and average commercial fishing intensity over time (1990 to 2015). Darker shading indicates higher fishing intensity

Fishery

Commercial Harvest

Barramundi in the Southern GoC stock are taken commercially as part of the Gulf of Carpentaria Inshore Fin Fish Fishery (GOCIFFF), which extends from Slade Point near the tip of Cape York Peninsula to the Queensland/Northern Territory border. The GOCIFFF is a multi-species fishery that includes an inshore (N3 symbol) commercial net fishery that harvests inshore species such as barramundi and king threadfin, and an offshore (N9 symbol) commercial net fishery that targets offshore species such as shark and grey mackerel. The inshore N3 fishery uses set mesh nets (i.e., gill nets) in rivers, on foreshores and in more offshore waters out to seven nautical miles. See Roelofs (2003) and Ward (2003) for a detailed description of the GOCIFFF, including commercial fishing methods. The GOCIFFF is managed separately from the East Coast Inshore Fin Fish Fishery, with different management arrangements applying in each fishery. The GOCIFFF requires a Wildlife Trade Operation (WTO) for export approval and protected species accreditation under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999,* to demonstrate that the fishery is operating under national sustainability guidelines.

Since 1989, commercial catches of barramundi have been recorded through a compulsory daily logbook, referred to as CFISH. The annual catch of barramundi varies spatially within the Southern GoC stock (**Figure 1**) and also varies temporally. Commercial inshore netting symbols (N3) in the GOCIFFF have reduced over time, from 109 in 1998 (Queensland Government 2004) to 87 in 2008 (Queensland Government 2009) to 85 in 2015. N3 symbols are attached to commercial fishing boat licences, with between one and three N3 symbols per licence. The number of active licences (i.e., those reporting catching barramundi) in the GOGIFF is variable between years – ranging from 91 active licences in 1993 to 64 active licences in 2015.

Recreational and Indigenous Harvest

Barramundi is a key target species for recreational anglers in north Queensland, taken by line fishing in freshwater, estuarine and marine waters. Effort within the recreational fishery is not limited or licensed, although the management arrangements of minimum and maximum size limits, seasonal (spawning) closures and an in-possession limit of five applies to recreational fishers.

The scale of Queensland recreational fishing for barramundi (effort, catch, release and harvest) is estimated through telephone-diary survey methods (Webley *et al.* 2015). The 2013/14 recreational fishing survey estimated that 174,000 barramundi were caught across Queensland, of which 132,000 were released after capture and 42,000 were kept (Webley *et al.* 2015); noting that these estimates have moderate standard errors and should be used with caution. Possession limits and size limits were the major reasons for the high release rate (i.e., 76%) of captured barramundi. Based on an average individual fish weight of 4.21 kg, Webley *et al.* (2015) estimated a recreational harvest weight of barramundi for Queensland-based fishers of 131 tonnes (compared to a total commercial harvest across Queensland in 2014 of 762 tonnes).

Recreational fishing catch data were not used in the current stock assessment due to an insufficient temporal record and the necessity for assumptions on post-release survival.

Management

Key current management arrangements within the GOCIFFF for the N3 fishery that are relevant to barramundi include (Fisheries Regulation 2008):

- a minimum size limit of 58 cm
- a maximum size limit of 120 cm
- a seasonal (spawning) closure preventing the harvest of barramundi and all commercial river set-net fishing between 7 October and 1 February
- limited number of commercial net fishing symbols: currently 85 N3 symbols
- mesh size limitations: 160 mm to 215 mm for rivers, creeks and nearshore waters; 160 mm to 165 mm for offshore waters (to seven nautical miles)
- net length limitations: a combined net length not longer than 360 m in rivers and creeks; and a combined net length not longer than 600 m in nearshore waters; a combined net length not longer than either 300 m (one N3 symbol on a licence) or 600 m (more than one N3 symbol on a licence) in offshore waters
- legislated net attendance rules while fishing
- various spatial closures to commercial and recreational fishing.

There have been numerous changes in the management arrangements for inshore net fisheries across Queensland (see Appendix A – Compilation of management arrangements for Queensland barramundi). Several key management actions (e.g., changes to the minimum size limit and introduction of the maximum size limit and the seasonal spawning closure) have been incorporated into the current stock assessment via changes in selectivity because of their likely effect on the model dynamics – see below.

Stocking

Barramundi is a species which is reared in hatcheries then stocked in considerable numbers as fingerlings into many impounded waterways throughout Queensland. The escape of these fish during floods is a complication for the assessment and management of barramundi stocks, due to the unknown contribution these fish make to the wild estuarine populations. Certain combinations of stocking practices and flood events have led to major impacts on the total barramundi catch and fishery monitoring data on the Queensland east coast (Wesche *et al.* 2013). Information on stocked barramundi in Queensland (see Appendix B - Collated information on stocked barramundi for each genetic stock in Queensland) suggests that the stocking of fingerlings is not likely to have significantly affected the Southern GoC stock within the time frame of the current assessment.

Methods

Source Data

Catch and effort

The current stock assessment model is driven by fishing effort and fitted to catch. Model predictions are sensitive to the full history of fishing; therefore it is important to reconstruct this history to the extent that is possible. There is anecdotal evidence that prior to 1981, barramundi catches were in decline in the Gulf of Carpentaria due to increased fishing pressure through the 1970s (Gribble 2004). This was the impetus for management changes in 1980 (e.g., closed season, limited entry, recreational possession limit; see Appendix A).

The catch and effort history of the fishery is divided in time into three phases. The most recent is the CFISH logbook phase. CFISH is a compulsory daily logbook for commercial and charter fishers, and covers the period 1990-2015 for the GOCIFFF. Prior to CFISH, covering 1981-1989, we refer to as the TRAP phase, which draws on voluntary research logbook data (GN01 and GN02) collated by the Tropical Resource Assessment Program (TRAP). The earliest phase we term “historical” and is a 1954-1980 reconstruction based on available published literature.

CFISH (1990 to 2015)

Annual commercial catch and effort data for barramundi were extracted from the Fisheries Queensland CFISH logbook database.

TRAP (1981 to 1989)

Gribble (2004) collated catch and effort data for barramundi from a voluntary monthly logbook program for net fishers working in the Gulf of Carpentaria (Quinn 1984) – known as GN01 and GN02 logbooks or colloquially as “production returns”. In the current assessment, we use data compiled by Lew Williams (DAF) from statistical grids B, C, and D, which approximately corresponds to the spatial extent of the Southern GoC stock, as defined for the Status of Australian Fish Stocks report.

Historical (1954 to 1980)

There is no data on fishing effort for Gulf of Carpentaria net fisheries prior to the voluntary monthly logbooks introduced in 1981. However, there are oral histories recounting the development of prawn and net fisheries in the Gulf of Carpentaria and a few point-in-time references for barramundi catch. Information in Dunstan (1959), Quinn (1984) and the oral histories of Queensland net fishers collected by Darcey (1991) were used to reconstruct a time-series of estimated fishing effort (number of days) between 1954 and 1980. Dunstan (1959) reports the total Gulf catch for 1955 as 22,389 lb and that in 1957, the total catch exported from the Gulf as approximately 200,000 lb headed and gutted fish, of which 70% was barramundi. This equates to 9.85 tonnes and 87.75 tonnes whole wet weight in 1955 and 1957 respectively, assuming 70% barramundi, a conversion factor of 1.4 between headed-and-gutted fish to whole wet weight and that the majority of the catch was taken from the Southern GoC stock. Fishing effort in 1955 and 1957 was inferred based on a catch:effort ratio of 38.1 kg/day, which was derived from the 1981 TRAP data. Fishing effort in 1955 was inferred to be 257 days, and in 1957 was inferred to be 2,295 days. We assumed no expansion of the fishery between 1957 and 1970, but thereafter a rapid increase in the effort and catch of barramundi, peaking in 1977, based on barramundi landings reported in Australian fisheries statistics and the development of Karumba and the GoC prawn fishery. As such and for simplicity, we assumed a linear increase in effort between 1970 (i.e., 2295 days) and 1977 (i.e., 25598 days) and then a linear decline to 21,304 days of effort in

1981, as reported in the TRAP data (Gribble 2004). **Figure 2** displays the catch history for the TRAP and CFISH phases. **Figure 3** displays the effort history for the historical, TRAP and CFISH phases.

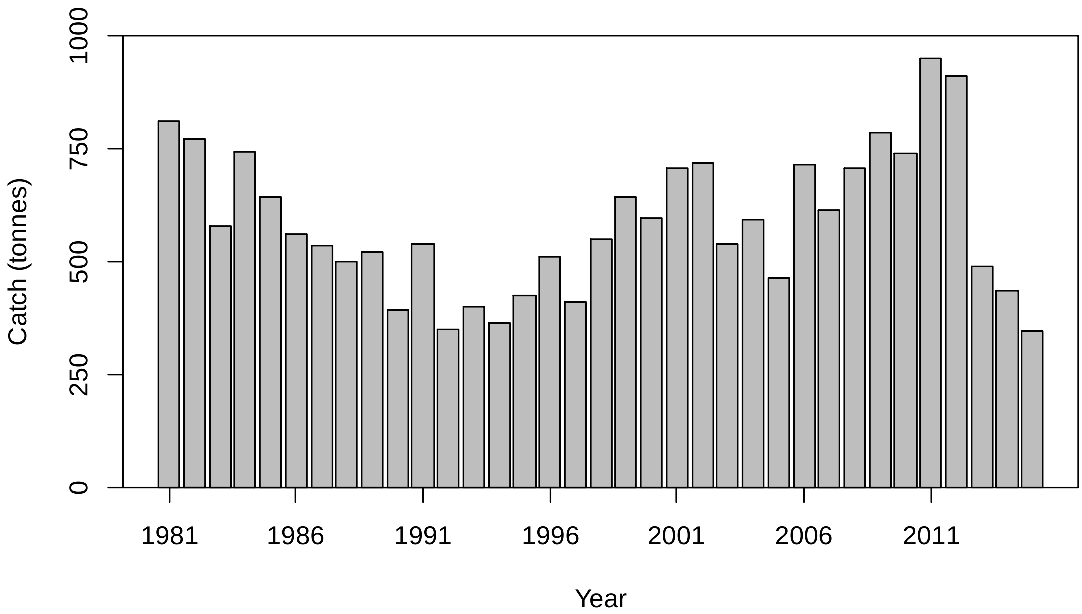


Figure 2 - Annual catch of the Southern Gulf of Carpentaria barramundi stock based on TRAP voluntary logbooks (1981 to 1989); and CFISH commercial logbooks (1990 to 2015)

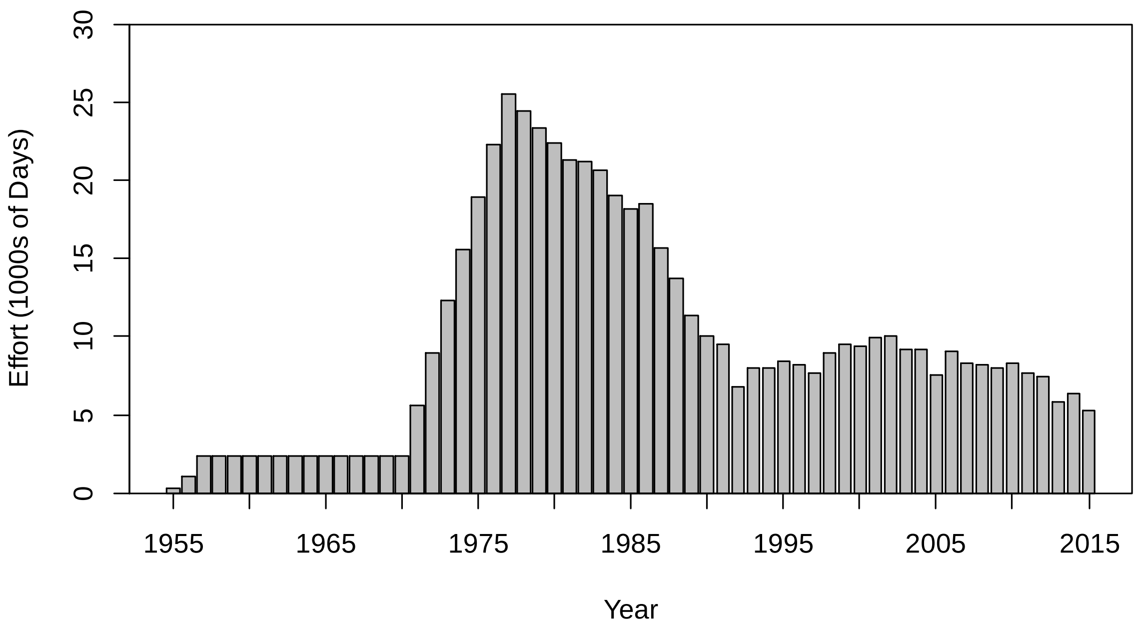


Figure 3 - Annual effort (days fished) in the Southern Gulf of Carpentaria barramundi stock based on reconstructed historical (1955 to 1980); TRAP voluntary logbooks (1981 to 1989); and CFISH commercial logbooks (1990 to 2015)

Length and age data

Length- and age-frequency data were extracted from the Fisheries Queensland Long Term Monitoring Program database. The length information represented the total length (TL) of 20,824 barramundi measured by the program between 2000 and 2015. Age represented the age-class of 8,186 barramundi aged by the program between 2000 and 2015 based on visual assessment of thin-sectioned otoliths. See Fisheries Queensland (2010) for protocols.

Selectivity over time

Selectivity was primarily based on the field study by Hyland (2007), who set gill nets with meshes of various sizes in Princess Charlotte Bay and Trinity Inlet. The selectivity estimation approach followed Sparre *et al.* (1989) with statistical analysis based on Millar and Holst (1997) and Millar and Fryer (1999). Hyland (2007) produced a three-parameter selectivity curve. Two of these parameters we fix at values estimated by Hyland (2007). The third parameter is the mesh size used in the fishery. To determine this in the Southern GoC stock, information was gathered from:

- research observers on commercial vessels during an FRDC project on the effects of net fishing (Halliday *et al.* 2001)
- the Fisheries Queensland commercial fishery observer program
- conversations by DAF staff (W Hagedoorn and J Robins) with commercial fishers about the mesh size of nets used
- mesh sizes reported in the compulsory commercial logbook (i.e., CFISH).

In the Gulf of Carpentaria, monofilament gill nets are used exclusively. Although observed mesh size ranged from 162 mm to 210 mm (depending on where fishing was occurring), fishers in the Southern GoC most commonly use 162 to 165 mm mesh of 50 or 70 ply (i.e., 6½ inch) depending on location.

Maturity, fecundity and proportion female

Female fecundity and male maturity are based on the results presented in Davis (1984) and Davis (1982) respectively. Davis (1984) found an exponential relationship between total length and fecundity:

$$\mathrm{fec}(l) = \eta \exp(\zeta l)$$

where $\eta = 0.3089$ and $\zeta = 0.0035$. This was converted to fecundity-at-age by integrating over lengths-at-age:

$$\mathrm{fec}_a = \int_a^{a+1} \mathrm{fec}\big(l_\infty - l_\infty \exp\big(-\kappa(\alpha - a_0)\big)\big)\ d\alpha$$

Based on data presented in Davis (1982), we estimated the proportion of males that were sexually mature at lengths of 50, 55, 60, 65, 70, 75, 80 and 85 cm as 0, 25, 25, 64, 73, 91, 96 and 100% respectively, denoted as $\mathrm{mat}_i, i = 1,..,8$. This approximates a cumulative distribution function (CDF). The transformation from fecundity-at-length to fecundity-at-age needs to be performed on a probability distribution function; that is, the derivative of the CDF. We calculate this as

$$\mathrm{matdif}_i = \frac{\mathrm{mat}_{i+1} - \mathrm{mat}_i}{\sum_{i=1}^{7} \mathrm{mat}_{i+1} - \mathrm{mat}_i}, \quad i = 1,..,7$$

For male maturity, lengths were mapped to ages via an Age-Length Key (ALK) using standard methodology (Kimura, 1977). This ALK is a matrix p_{ij}, where i runs from $1, \dots, M$, where M is the number of ages and j runs from $1, \dots, N$, where N is the number of length bins. In this case, $N = 7$. The age-transformed result is

$$\text{mat'}_i = \sum_{j=1}^{7} p_{ij}\,\text{matdif}_j$$

This is then integrated to recover the age-based maturity:

$$\begin{cases} \text{mat}_1 = \text{mat'}_1 \\ \text{mat}_a = \sum_{i=2}^{a} \text{mat}_{i-1} + \text{mat'}_i\,, \qquad a = 2, .., a_{\max} - 1 \end{cases}$$

Proportion female was based on a curve fitted to LTMP gender-at-age data with the following form:

$$\text{Fem}_a = \alpha + \gamma \big/ \left(1 + \exp\left(-\beta(a - \delta)\right)\right)$$

The fitted values were -0.279, 0.2865, 1.246 and 5.073 for α, β, γ and δ respectively.

Table 1 - Values of meta parameters used in the Southern GoC barramundi stock assessment model

Symbol	Name	Value
M	Natural Mortality	0.2
κ	Growth rate	0.16
l_∞	Asymptotic length (cm)	150
ESW	LTMP effective sample weighting	40
a_{min}	Minimum age class (years)	2
a_{max}	Maximum age class (years)	30
$a_{min-obs}$	Youngest age class used in model fitting	2
$a_{max-obs}$	Oldest age class used in model fitting	12
T	Number of years	61

Model Description

The model is a traditional age-structured population model with an annual time step. It is driven by effort, and fitted to total catch, under the assumption that abundance is proportional to catch rate. The only non-standard element is a distinction between the sexes with respect to reproduction. A sex-ratio curve (as a function of age) was fitted, and egg production is given by the product of mature males and fecund females. Values of meta parameters used throughout the model are given in **Table 1**.

Population dynamics are given by

$$N_{a+1}(t+1) = \begin{cases} N_a(t)\exp\left(-M + s_a q(t) e(t)\right), & a = a_{\min}, \dots, a_{\max} \\ N_a(t), & a = 0, \dots, a_{\min} - 1 \end{cases}$$

where t is the year (running from $t = 1,..,T$), a denotes age of the fish in years, $a_{\min}$ and $a_{\max}$ are the youngest and oldest modelled ages respectively, M is the annual natural mortality rate, s_a is the selectivity at age, $q(t)$ is the catchability at time t and $e(t)$ is the effort in year t measured in number of days fished.

Catchability is time dependent, given by

$$q(t) = \exp(q_{\text{base}}) + \exp(q_{\text{base}}) \times t \times\ q_{\text{inc}}$$

where q_{base} is the natural logarithm of the catchability in 1955 and q_{inc} is the factor by which the catchability increases per year, as a proportion of the 1955 catchability.

Selectivity at age, s_a, was transformed from selectivity-at-length based on Hyland (2007). The "free parameter" in the Hyland curve was mesh size, ϕ, which we varied over time in three phases. These phases were chosen as a simplification of the complex changes to historical management arrangements, combined with mesh size data where available. Phase one was 1955 through to 1988. During this period, there was no upper size limit for barramundi and the minimum legal size was 50.8 cm. Phase two was 1989 through to 1996. In 1989, a maximum legal size of 120 cm was introduced (via regulation of mesh size) and CFISH data indicate a combination of 6-inch and 6.5-inch mesh sizes were used. The third phase was 1997 through to 2015. During this phase, the minimum mesh size was raised to 6.5-inch and CFISH data indicated the clear majority of fishers were using this mesh size.

Selectivity-at-length was then given by

$$s(l) =\ \exp\left(-\frac{(l - \phi\iota_1)^2}{2\ \iota_2\phi^2}\right)$$

where $\iota_1 = 5.2,\ \iota_2 = 0.619$ and $\phi = 15.24, 16.51$ and 20.32 for phase one, two and three respectively.

Selectivity-at-age was then calculated by

$$s_a = \int_a^{a+1} s\big(l_\infty - l_\infty \exp(-\kappa(\alpha - a_0))\big)\ d\alpha$$

where $l_\infty = 150$, $a_0 = -0.5$ and $\kappa = 0.16$ for all scenarios, except where indicated as $\kappa\ Low$ where $\kappa = 0.15$.

In order to explore the sensitivity of model results to dependence on the growth curve, an alternative approach to selectivity-at-age was developed. The selectivity-at-length is generated from the established curves for the way selectivity-at-length changes through time (described above). These curves were transformed to a probability density (i.e., they were standardised so that they integrated to one). That is, given selectivity-at-length, $s_l, l = 1, \ldots, M$ we generate

$$s_l' = \frac{s_l}{\sum_{j=1}^{M} s_j}$$

The mapping is then applied:

$$s_a' = \sum_{j=1}^{M} p_{aj} s_a'$$

The resulting curve is a transformed version of selectivity-at-age, because the probability density standardisation has not yet been undone. This curve is then back-transformed by multiplying by a factor such that the maximum value is equal to one, to obtain the final selectivity at age, s_a. As in the male maturity case, the ALK does not include sufficient data to establish a mapping for the first year. A value was chosen by inspection. On the transformed scale this value was 0.05. The actual value of selectivity in the first year after back-transformation is shown in **Figure 13**, Appendix C.

Reproduction is given by

$$N_0(t) = \frac{P(t-1)}{\alpha + \beta\, P(t-1)} (\epsilon(t) - \; 0.5\sigma^2)$$

where $P(t)$ is egg production in year t given by

$$P(t) = \left(\sum_{a=a_{\min}}^{a_{\max}} (1 - \mathrm{fem}_a)\, \mathrm{mat}_a N_a(t) \right) \left(\sum_{a=a_{min}}^{a_{max}} \mathrm{fem}_a\, \mathrm{fec}_a N_a(t) \right)$$

where fem_a is the proportion of female-at-age, $\mathrm{fec}_a$is the female fecundity-at-age, and mat_a is the male maturity-at-age as defined previously.

Catch (in numbers) at age is given by

$$C_a(t) = \frac{s_a q(t) e(t)}{M + s_a q(t) e(t)} N_a(t) \left(1 - \exp\left(-\left(M + s_a q(t) e(t)\right)\right)\right)$$

and catch in weight is then

$$\hat{C}(t) = \sum_a w_a C_a(t)$$

where w_a is the weight-at-age in kilograms.

The model is fit to total annual catch between 1981 and 2015 and the LTMP frequency-at-age data, although only frequency-at-age data between 2008 and 2015 were used in the fitting process as these years each have greater than 1000 fish measured for total length and greater than 450 fish aged from otolith thin-sections. The LTMP frequency-at-age data were constructed according to standard LTMP protocols (Fisheries Queensland 2010).

The model-predicted frequency-at-age is given by

$$\hat{A}_a(t) = \frac{C_a(t)}{\sum_{a=a_{min-obs}}^{a_{max-obs}} C_a(t)}$$

for $a = a_{min-obs}, \ldots, a_{max-obs}$ representing the smallest to largest fitted age classes.

The model is fitted in a standard statistical fashion using a Maximum *a Posteriori* (maximum likelihood with priors). Steepness, h, and virgin recruitment, $N_0(0)$, were used as leading parameters, with the standard translation to α and β:

$$\alpha = \frac{\sum_a N_a(0)}{N_0(0)} \left(\frac{1-h}{4h}\right)$$

and

$$\beta = \frac{5h - 1}{4h N_0(0)}$$

The negative log likelihood components are as follows. Firstly, the prior on the stock-recruitment residuals:

$$l_1(\theta) = \sum_{t=1}^{T-1} \log(\sigma) + \frac{0.5\epsilon(t)^2}{\sigma}$$

Secondly, the likelihood for the catch observations:

$$l_2(\theta) = \sum_{t\in\hat{C}(t)} \log\tau + 0.5\left(\hat{C}(t) - C(t)\right)^2/\tau$$

Thirdly, the likelihood for the frequency-at-age data:

$$l_3(\theta) = -\sum_{t\in A_a(t)} \sum_{a\in A_a(t)} ESW\ A_a(t) \log \hat{A}_a(t)$$

where ESW is the effective sample weighting of the LTMP age-frequency data. ESW is a relative weighting factor used to adjust how much importance the model places on age-frequency data in comparison to the annual catch data.

Parameter estimation was conducted by minimising the negative log likelihood using ADMB. One million Markov chain Monte Carlo (MCMC) simulations were then conducted for each sensitivity test using ADMB.

We define Egg Production Ratio (EPR) as the ratio of the average egg production over the last seven years of the model (i.e., 2009 to 2015) to the egg production in 1954:

$$\mathrm{EPR} = \frac{1/_7 \sum_{t=T-6}^{T} P(t)}{P(0)}$$

A seven-year average was chosen to construct an indicator that was robust to the presence of strong environmental variation.

We also define an equilibrium version of the EPR. This is the ratio of egg production over the last seven years of the time series to the theoretical egg production at Maximum Sustainable Yield (MSY). MSY is calculated by simulating the fishery into the future with all parameters fixed at their estimated values and optimising yield over all possible fishing mortality rates. We denote the egg production at optimal fishing mortality as P_{MSY}. The equilibrium EPR is then

$$\mathrm{EPR}_{\mathrm{MSY}} = \frac{1/_7 \sum_{t=T-6}^{T} P(t)}{P_{\mathrm{MSY}}}$$

We also consider the ratio of current fishing mortality to the fishing mortality at MSY. This is

$$FR = \frac{F(T)}{F_{\mathrm{MSY}}}$$

This quantity was calculated based on the last year only (i.e., 2015). EPR is a measure of cumulative historical depletion, whereas FR is a measure of current practice, hence the different approach to calculating these indicators.

It should be noted that because recruitment is defined as two year olds, lower natural mortality values are more appropriate than with a model defining recruitment to be birth or one year of age (mortality is significantly higher during the early months of life).

Key assumptions of the model are:

- Abundance is proportional to raw annual catch rate.
- Selectivity is representative in each of the three phases of catch and effort.
- Egg production is proportional to the product of the number of mature males and the fecundity of females.
- The sex ratio does not change over time.
- The data collected by Davis (1982 and 1984) on maturity and fecundity-at-length are spatially and temporally representative.

Scenario exploration

We explored the sensitivity of the model to:

- Steepness in the stock recruitment curve
- Growth rate in the von Bertalanffy growth curve
- Selectivity-at-age
- LTMP age-frequency data
- Natural mortality
- Catch history
- Catchability increase

Sensitivity to stock-recruitment steepness was explored by using a variant of the model in which steepness was fixed at a range of values, and natural mortality was estimated. The steepness values (h) we explored were: 0.5, 0.6, 0.7, 0.8 and 0.9.

The growth rate parameter values used were 0.15 and 0.16.

Selectivity-at-length was fixed according to the Hyland selectivity curve in the three phases of catch and effort as described previously. Three different calculations were explored to transform this to selectivity-at-age. The first two used the von Bertalanffy growth curve with the variation in growth rate. The third method relied on an Age-Length Key (ALK) derived from the LTMP length and age data collected from the Southern GoC stock.

The influence of the LTMP age-frequency data on the model was explored by weighting this likelihood at three different levels. An Effective Sample Weighting (ESW) of 40 was the default implying a relatively equal importance of catch observations and age-structure data for model fitting. Alternate values were 10, implying lesser relative importance of the age-frequency data for model fitting and 100, implying greater relative importance of the age-frequency data for model fitting.

The default natural mortality (M) was 0.2, with a lower value of 0.1 and a higher value of 0.25 considered. In addition, in the variant scenarios where steepness was fixed (i.e., 0.5 to 0.9), natural mortality was estimated.

The default for catch history was to use catch data from only the TRAP and the CFISH phases to fit the model (i.e., 1981 to 2015). For one of the 16 scenarios (Catch Fit All), the catch data for the full history of the fishery was used to fit the model (i.e., 1955 to 2015).

The yearly catchability increase proportion, q_{inc}, was estimated between bounds of 0.0 and 0.15.

This resulted in 16 scenarios. Full details, including comprehensive results and goodness of fit plots for all 16 scenarios are available in Campbell (2017). The most challenging parameter for which to obtain reasonable estimates was q_{inc}, which is the factor by which the catchability increases per year, as a proportion of the 1955 catchability. Of the 16 scenarios, three scenarios estimated q_{inc} without hitting its lower or upper bound, indicating a superior parameterisation. Of these three scenarios, two had good fits to catch and age data and are reported on here (i.e., h=0.8 scenario and h=0.9 scenario). To provide a sensitivity contrast for growth rate, we also added a 'h=0.8, k low' scenario in which q_{inc} hit the upper bound (0.15), and had reasonable fits to catch and age data. We included a scenario where the LTMP age-frequency data were down-weighted in the model fitting process (i.e.,$l_3(\theta)$), referred to as ESW low, in which q_{inc} hit the lower bound (0) and had reasonable fits to catch and age data. We also included a scenario (M high) where estimated steepness was close to 0.9 as a sensitivity contrast for this value of steepness. Thus, we present the results for five scenarios:

1. Steepness = 0.8, herein referred to as (h=0.8)
2. Steepness $= 0.8$, growth rate = 0.15 (h=0.8, κ low)
3. Steepness = 0.9 (h=0.9)
4. ESW = 10 (ESW low)
5. Natural Mortality = 0.25 (M high)

Assumptions and Limitations

Influences of rainfall/river flow

Flow was not explicitly incorporated into the current model. Therefore, the equilibrium outputs of the model (MSY, EPR_{MSY} and FR) are representative of the productivity of the stock (including, for example, growth-rate dependent productivity) under long-term average rainfall/river flow influences. This assumes historical rainfall has not changed systematically over the long term. If the stocks were to experience a prolonged period of drought (or flood) that is outside the range historically experienced (i.e., 1955-2015), then the equilibrium predictions would no longer apply.

Recreational harvest

Recreational harvest is not included in the model because of a lack of data at appropriate temporal and spatial scales comparable to the commercial data. In general, if additional harvest is consistently taken (by recreational fishers) above that which is modelled, the estimated MSY will be underestimated roughly in proportion to the underestimate of total harvest. This is because the model estimates parameters that are consistent with the observed amount of fish extracted from the population – if more fish were taken while the data against which the model is fitted remain constant (e.g., age-frequency data), alternative parameter values would be necessary (e.g., greater steepness in the stock recruitment curve, lower natural mortality and larger initial population size).

Minimum legal size

Minimum legal size limit was not explicitly applied in the model and differential fishing pressure at (total fish) length was modelled purely via selectivity, thus, in the model undersized fish are harvested according to the selectivity curve. In reality, selected but undersized fish are probably released but suffer an unknown discard mortality. This simplification is conservative as it assumes additional fishing pressure, and its effects on model output are likely to be small because the selectivity curves are relatively steep in the region around minimum size (i.e., 55-60 cm).

Use of raw effort as a model input

Raw effort (in days fished) was used to obtain fishing mortality, via an estimated linear catchability term $q(t)$. Ideally, standardised effort over the complete time series of the fishery would be used, but this is strongly influenced by management interventions, changes in gear technology, socio-economic drivers of fisher behaviour and river flow. Standardising to account for these factors would be complex and dependent on many unknown quantities, even for the CFISH data.

Results

Model outputs and estimated parameter values for each of the five scenarios are given in **Table 2**. The parameter estimates which led to the best fit correspond to the mode of the theoretical distribution which represents the maximum likelihood of all possible parameter values. Parameter estimates are given in **Table 4**. This distribution is approximated by Markov chain Monte Carlo, from which we draw the 20th, 50th (median) and 80th quantiles (**Table 5**). The Egg Production Ratio (EPR) ranged from 0.33 to 0.41 and the Maximum Sustainable Yield (MSY) ranged from 599 to 715 tonnes. Trajectories of the EPR for each scenario are plotted in **Figure 4**.

Table 2 - Model outputs (sustainability indicators) and estimated parameter values for alternate scenarios

	Scenario				
	h=0.8	h=0.8, κ low	h=0.9	M high	ESW low
h	0.80	0.80	0.90	0.92	0.95
M	0.26	0.33	0.21	0.25	0.20
N_0	390700	497920	329580	325190	307350
$q(t)$	-12.32	-12.51	-10.86	-11.25	-10.42
q_{inc}	0.088	0.150	0.0081	0.025*	0.000003
$l_1(\theta)$ SRR	-88.53	-90.50	-90.54	-90.42	-95.21
$l_2(\theta)$ catch	426.92	425.99	426.01	424.97	423.75
$l_3(\theta)$ LTMP age	516.56	515.82	514.94	517.00	131.41
EPR (Mode)	0.41	0.33	0.34	0.41	0.33
MSY tonnes (Mode)	599	611	687	642	715
EPR_{MSY} (Median)	2.16	1.75	1.91	2.75	2.05
FR (Median)	0.50	0.59	0.50	0.41	0.48

The goodness-of-fit to phase two (TRAP) and phase three (CFISH) catch data is given in **Figure 5**, and the goodness-of-fit to the phase one (Historical) catch data is given in **Figure 6**. Note that the Historical catch data were not included in the likelihood calculations ($l_2(\theta)$) for the five scenarios reported upon here. However, it is informative to see whether model-predicted values are in the same order of magnitude as the reconstructed estimates for the historical phase catch (1955 to 1980).

Goodness of fit to LTMP age-frequency data for the years 2008 to 2015 is given in **Figure 7** for the scenario where h=0.8. The goodness-of-fit plot to age-frequency data for the five scenarios presented in the current report were visually very similar to the example in Figure 7. Plots of fit to LTMP age-frequency for all scenarios are available in Campbell (2017).

In general, both the catch and age-frequency fits are quite good. Exceptions to this are the historical phase catch fit for ESW low, h=0.9 and, to a lesser extent, M high. This is related to the challenge in fitting q_{inc}: larger increases in catchability over time enabled the model to simultaneously fit TRAP-CFISH phase catches as well as historical phase catches. However, a high q_{inc}, was not always compatible with various model assumptions. In particular, scenarios which favoured a high steepness and smaller population solution were only able to achieve good fits to catch and age data with a lower q_{inc}, leaving the historical catch relatively poorly predicted. Even in the case of the two scenarios which fitted the historical catch quite well (the two scenarios with h=0.8), the period from 1970 to 1980 was over-predicted. A significant contributor to the challenge of fitting the historical catch data is the combined effect of changes in fisher practices and knowledge, management interventions, technology changes and socio-economic changes; these will have unfolded in a more complex manner than our linear model for increases in catchability can account for.

Another relatively poor fit was for the CFISH catch data for the last six years of the model, where catch was under- and over-predicted consistently across all scenarios. This is likely attributable to a lack of explicit modelling of environmental drivers during this period of large variability on Southern GoC river flows.

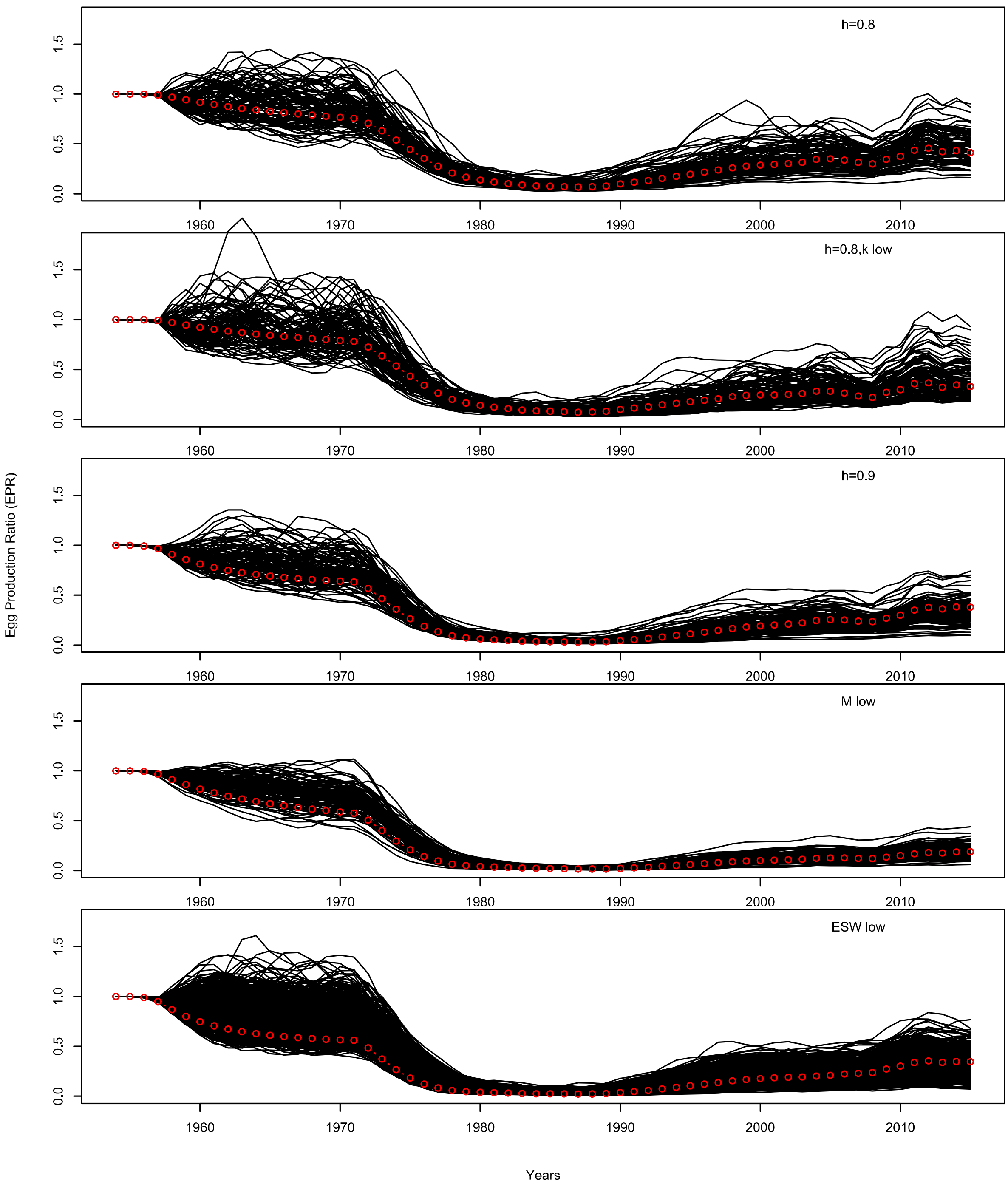


Figure 4 - Southern Gulf of Carpentaria barramundi annual Egg Production Ratio (EPR) for 1954 to 2015 relative to unfished equilibrium for each scenario; each trajectory represents a sample from the MCMC chain. The theoretical modal trajectory (i.e., the model outcome with the best fit) of the posterior distribution is represented by the red circles.

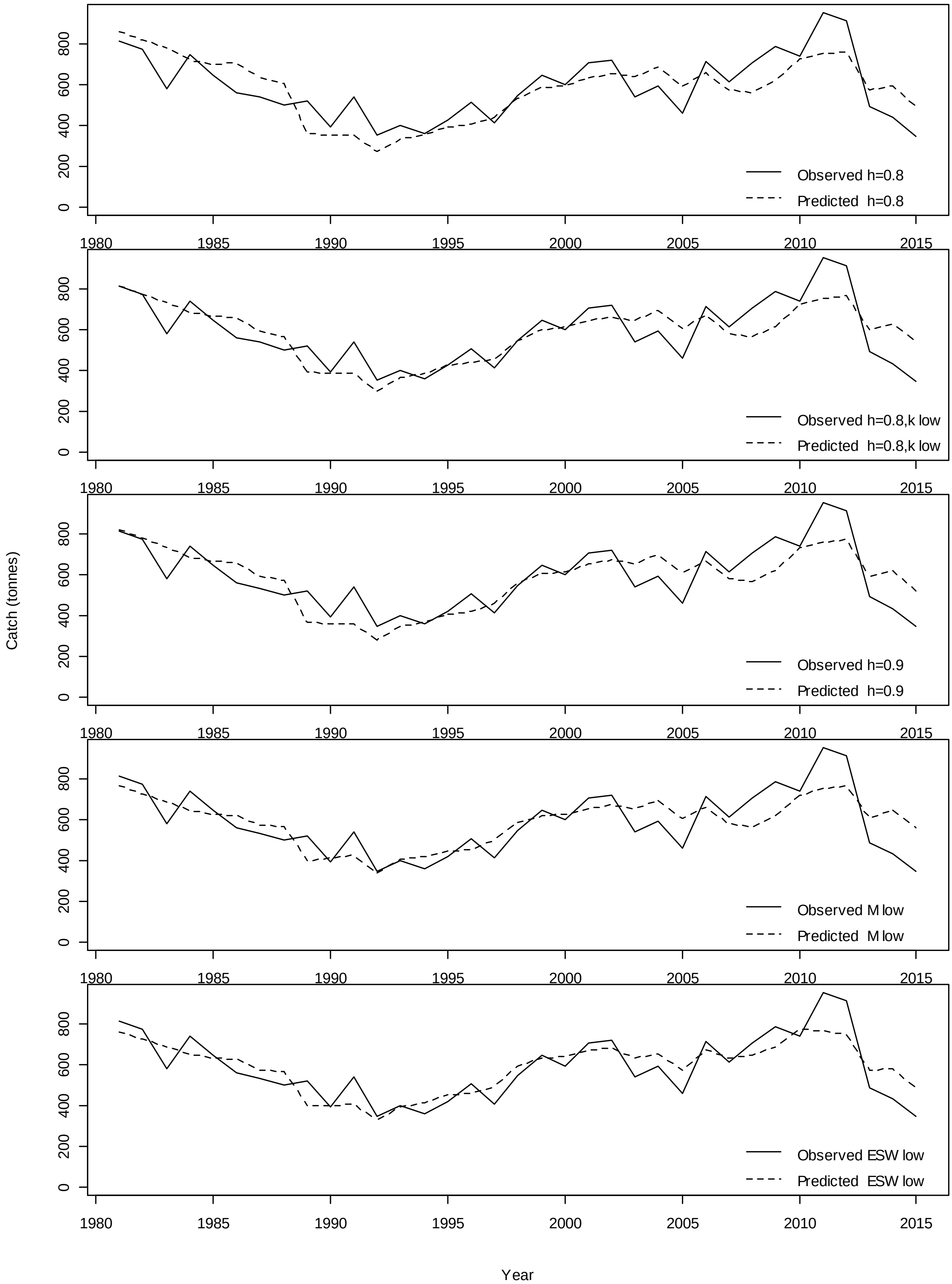


Figure 5 - Southern Gulf of Carpentaria barramundi annual catch fit for 1980 to 2015 for the observed catch and for the predicted catch for the modal trajectory for the five scenarios.

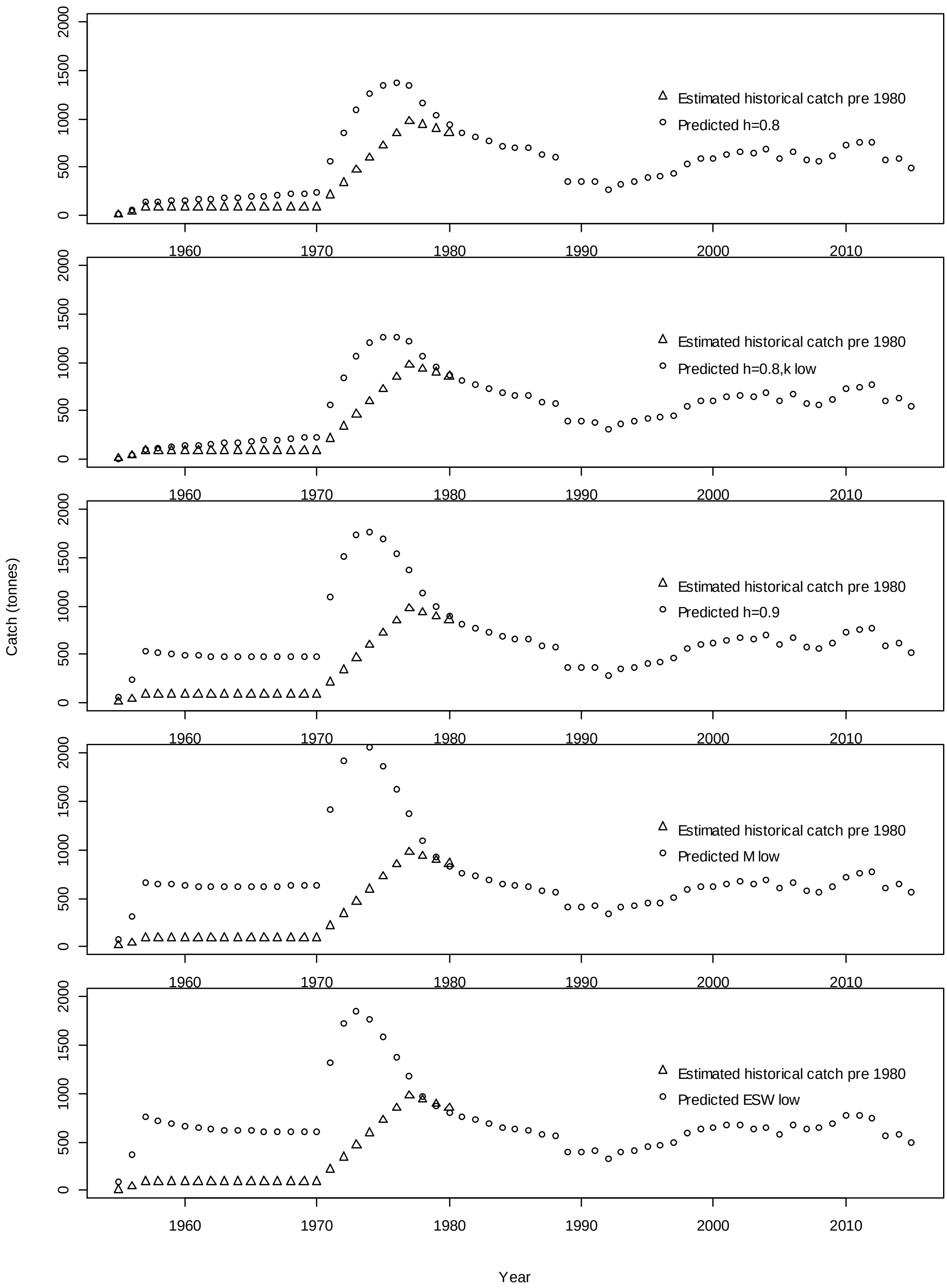


Figure 6 - Southern Gulf of Carpentaria barramundi annual catch fit for the estimated historical catch (1955 to 1980) and the predicted catch for the modal trajectory of the five scenarios

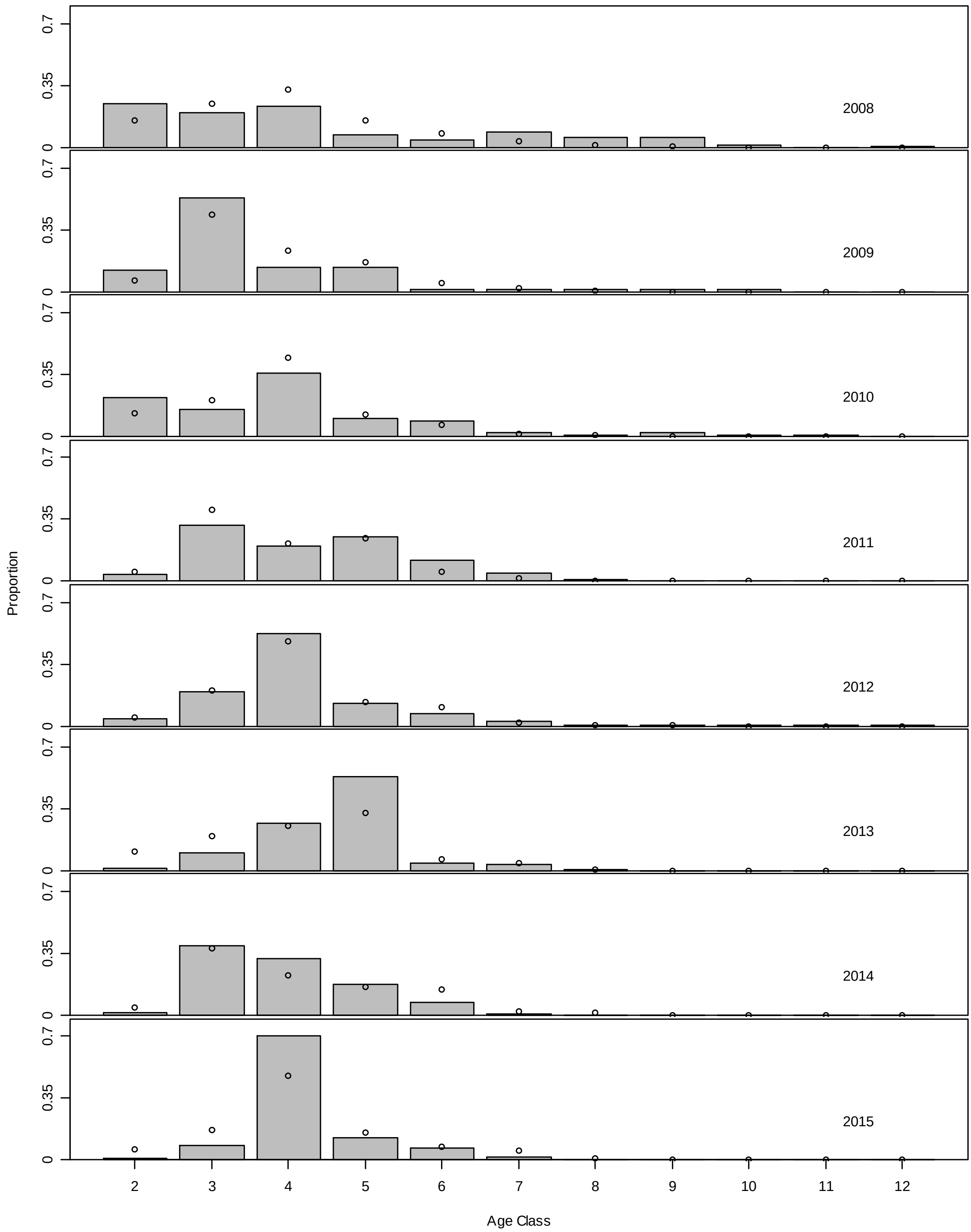


Figure 7 - Southern Gulf of Carpentaria barramundi annual age structures (2008 to 2015) for the observed (LTMP, indicated by grey bars) and model predicted (indicated by the open circles) for the scenario where h=0.8.

Discussion and Recommendations

All five scenarios have an EPR below 48%, which is the proxy in Commonwealth fisheries for the biomass that sustains Maximum Economic Yield (Stewardson, 2016). All five scenarios have an EPR that is above 20%, a common proxy for the biomass below which the risk to the stock is regarded as unacceptably high (the so-called limit reference point).

The Southern GoC barramundi stock experiences strong environmental forcing (e.g., from rainfall events and consequent river flows) which impacts on multiple biological processes, and none of these were explicitly modelled. The five scenarios presented here that had good to reasonable fits to catch and age data all had high steepness – a feature of highly productive stocks. It is possible that the model is insufficiently sophisticated to fit well to scenarios which represent populations that are less productive. For this reason, we recommend more weight is placed on the non-equilibrium indicator (i.e., EPR) than on the equilibrium-based indicators (i.e., MSY, EPR_{MSY}, and FR). This would be prudent given anecdotal evidence of significant stock decline during the historical phase (1955 to 1980).

The various management arrangements that have been introduced over the years appear to have brought the stock back from seriously depleted levels, while not yet achieving optimal levels for economic, social or environmental objectives. The magnitude of the recruitment residuals supports anecdotal and scientific evidence that the stock is strongly driven by the environment. As a consequence, fixed equilibrium-based targets for fishing mortality and biomass will involve lost opportunities during successive high flow years as well as unnecessary risk during successive drought years. However, operationalising an alternative to fixed equilibrium-based targets and disentangling historical overfishing from the effects of variable flow, would require explicit modelling of environmental drivers.

The LTMP age-structure data was of critical importance in obtaining the growth curve, the selectivity curve, the male maturity curve, the female proportion-at-age, and in estimating model parameters through the role of this data in quantifying mortality and general population dynamics. The importance of a long, continuous time-series of length- and age-structure, and gender data (such as that gathered by the LTMP) cannot be over emphasised.

Recommendations:

- Continue sampling length, age and gender information for barramundi, especially in the Southern GoC sufficient to capture variability within this spatially diverse stock.
- Improve CFISH logbook data (quality and detail). Details that would support effort standardisation should include mesh size(s), net length, placement, precise location fished and measures of effort for example, hours fished per day, number of retrievals, number of sets and net soak time. Details on the historical uptake of GPS, sounders, power net reels and other technology that affects fishing power should be collected.
- Validate CFISH logbook data
- Although not a major issue for the Southern GoC barramundi stock, all stocking events should be quantitatively recorded by Fisheries Queensland in a central database, including as a minimum: date, number of fish stocked, average length, and location of release. The population dynamics of barramundi stocks on the Queensland east coast are potentially confounded by stocked fingerlings, and without such data, quantitative assessment of other Queensland barramundi stocks (especially the NEC) will be compromised.

- Growth rates play an important role in stock assessment, and variation in growth rates can potentially lead to a different outcome. Data sources that assist with estimating spatial and temporal variation in fish growth should be sourced.
- The inclusion of environmental drivers, such as river flow in stock assessment, should continue to be a goal for barramundi, with ongoing research and data collection to support this.

References

Australian Government 2007. Commonwealth Fisheries Harvest Strategy: Policy and Guidelines. Department of Agriculture. Canberra, Australia. 55 pp. http://www.agriculture.gov.au/fisheries/domestic/harvest_strategy_policy

Cairns Post (1992). Anglers wary of barra limits. 21/03/1992

Campbell, A.B., O'Neill, M.F. and Officer, R. (2008). Assessment of the barramundi fishery in Queensland, 1989-2007. Queensland Department of Primary Industries and Fisheries, Southern Fisheries Centre, Brisbane. 27 pp.

Campbell, A. (2017). *Barramundi stock assessment enhancement -Southern Gulf of Carpentaria, phase 2a extension follow up*. The Poisson Institute, West End. 254 pp.

Darcey, J. (2015). Oral history of the Australian Fishing Industry. Queensland. Final Report to FRDC for Project Number 1987-021.90. 305 pp.

Davis, T.L.O. (1982). Maturity and sexuality in barramundi, *Lates calcarifer* (Bloch), in the Northern Territory and South-eastern Gulf of Carpentaria. *Australian Journal Marine and Freshwater Research* 33, 529-45.

Davis, T.L.O. (1984). Estimation of fecundity in barramundi *Lates calcarifer* (Bloch), using an automatic particle counter. *Australian Journal Marine and Freshwater Research* 35, 111-118.

DPI (1989). *Changes in fisheries management*. Ministerial Media Release, Department of Primary Industries, Queensland, 17/02/1989.

Dunstan, D.J. (1959). The barramundi *Lates calcarifer* (Bloch) in Queensland waters. Division of Fisheries and Oceanography Technical Paper. 22 pp.

Elmer, M. (1987). Barramundi (*Lates calcarifer*) fishery management in Queensland, Australia. In: Management of wild and cultured sea bass/barramundi (*Lates calcarifer):* Proceedings of an international workshop held at Darwin, N.T. Australia, 24-30 September 1986. ACAIR Proceedings No. 20. Pages 96-98.

Fisheries Queensland (2010). Fisheries long term monitoring program sampling protocol - barramundi (2008 onwards) Section 1. Department of Employment, Economic Development and Innovation, Brisbane. 10 pp.

Fisheries Regulation (2008). https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/F/FisherR08.pdf

Garrett, R.N. (1997). Biology and harvest of tropical fishes in the Queensland Gulf of Carpentaria gillnet fishery. Information Series QI98018. Queensland Department of Primary Industries. 119 pp.

Garrett, R.N. and Russell, D.J. (1982). Pre-management investigations into the barramundi *Lates calcarifer* (Bloch) in northeast Queensland waters: a report to the fishing industry research committee. Queensland Department of Primary Industries, Cairns. 38 pp.

Glaister, J.P. (1990). Barramundi. In: *Legal Sizes and Their Uses in Fisheries Management*. Australian Society for Fish Biology Workshop, Lorne, Victoria, 24 August 1990. Ed. D.A. Hancock. Bureau of Rural Resources Proceedings No. 13. Australian Government Publishing Service, Canberra. Pages 73-77.

Gribble, N.A. (2004). Tropical Resource Assessment Program (Queensland inshore fish stocks): Phase I, Collation and assessment of available fisheries information and, Phase II, Model application and validation. Final Report for FRDC Project 1999/125. Department of Primary Industries, Queensland. 351 pp.

Gribble, N., Welch, D., Garrett, R., Higgs, J. and Whybird, O. (2005). Draft 1981 - 2004 assessment of the barramundi fishery in Queensland. Department of Primary Industries and Fisheries, Queensland, Cairns. 62 pp.

Hall, N.G., de Lestang, P., *et al*. (2008). Progress towards development of a sex, habitat and age-structured stock assessment model for Australian barramundi fisheries. In: *Managing, Monitoring, Maintaining and Modelling Barramundi*. Eds. Grace, B., Handley, A. and Bajhau, H. Northern Territory Government: Darwin. Pages 50-66.

Halliday, I., Ley, J., Tobin, A., Garrett, R., Gribble, N. and Mayer, D.G. (2001). *The effects of net fishing: addressing biodiversity and bycatch issues in Queensland inshore waters*. Final Report to FRDC for Project Number 97/206. Queensland Department of Primary Industries, Brisbane. 103 pp.

Halliday, I.A., Saunders, T., Sellin, M.J., Allsop, Q.A., Robins, J.B., McLennan, M. and Kurnoth, P. (2012). *Flow impacts on estuarine finfish fisheries of the Gulf of Carpentaria*. Final Report for FRDC Project No. 2007/002. Queensland Department of Agriculture, Fisheries and Forestry, Brisbane. 76 pp.

Hyland, S.J. (2007). *Mesh selectivity for barramundi*. DPI&F Project Report. Department of Primary Industries and Fisheries, Queensland. Cairns. 12 pp.

Jerry, D.R., Smith-Keune, C., *et al*. (2013). *Vulnerability of an iconic Australian finfish (barramundi - Lates calcarifer) and aligned industries to climate change across tropical Australia*. Final Report for Fisheries Research and Development Corporation Project No 2010/521. James Cook University, Townsville. 222 pp.

Keenan, C.P. (1994). Recent evolution of population structure in Australian barramundi, *Lates calcarifer* (Bloch): An example of isolation by distance in one dimension. *Australian Journal Marine and Freshwater Research* 45, 1123-1148.

Haysom, N.M. (2001). *Trawlers, Trollers and Trepangers. A history of the Queensland Fishing Industry pre-1988*. Queensland Department of Primary Industries Publications. Brisbane.

Kimura, D.K. (1977). Statistical assessment of the age-length key. *Journal of the Fisheries Research Board of Canada* 34, 317-324.

Moore, R. (1979). Natural sex inversion in the Giant Perch (*Lates calcarifer*). *Australian Journal Marine and Freshwater Research* 30, 808-813.

Pearce, M. (2008). A brief history of stocking management in Queensland. In: *Managing, Monitoring, Maintaining and Modelling Barramundi*. Proceedings of the National Barramundi Workshop, 6-8 July 2005, Darwin, Northern Territory. Eds. Grace, B., Handley, A. and Bajhau, H. Northern Territory Government, Darwin. Pages 39-41.

QDHM (1959). Toss that tiddler! Minimum size of fishes and crustaceans that may be taken in Queensland waters. Queensland Department of Harbours and Marine.

QFMA (1987). Management of barramundi in Queensland. Queensland Fish Management Authority leaflet.

QFMA (1990). *A review of the east coast barramundi fishery and proposed management measures. A discussion paper.* Queensland Fish Management Authority, Brisbane. 17 pp.

Queensland Government (2004). Fisheries (Gulf of Carpentaria Inshore Fin Fish) Management Plan 1999. Reprinted No. 2 (June 2004). Brisbane, Queensland. 80 pp.

Queensland Government (2009). Gulf of Carpentaria Inshore Fin Fish Fishery Review. Issues and options paper. Department of Employment, Economic Development and Innovation, Brisbane. 22 pp.

Quinn, R. (1984). Successful barramundi logbook program assists management. *Australian Fisheries*, October, 11-12.

Robins, J., Mayer, D.G., Staunton-Smith, J., Halliday, I., Sawynok, B. and Sellin, M.J. (2006). Variable growth rates of the tropical estuarine fish barramundi *Lates calcarifer* (Bloch) under different freshwater flow conditions. *Journal of Fish Biology* 69, 379-391.

Roelofs, A. (2003). Ecological assessment of the Gulf of Carpentaria inshore fin fish fishery. A report to Environment Australia on the sustainable management of a multi-species tropical gillnet fishery. Department of Primary Industries, Queensland. 94 pp.

Rimmer, M.A. and Russell, D.J. (1998). Survival of stocked barramundi, *Lates calcarifer* (Bloch), in a coastal river system in far northern Queensland. *Bulletin of Marine Science* 62, 325-336.

Russell, D.J. (1988). *An assessment of the east Queensland inshore gillnet fishery*. Queensland Department of Primary Industries, Cairns. 56 pp.

Russell, D.J. (2014). *Lates calcarifer* wild stocks: Their biology, ecology and fishery. *In: Biology and Culture of Asian Seabass Lates calcarifer.* Ed. D.R. Jerry. CRC Press, Taylor and Francis Group. Pages 77-101.

Russell, D.J. and Hales, P. (1993). A survey of the Princess Charlotte Bay recreational barramundi fishery. QI93049. Queensland Department of Primary Industries, Cairns. 18 pp.

Saunders, T., Whybird, O. and Newman, S. (2016). Barramundi *Lates calcarifer*. In: Status of Australian Fish Stocks Reports 2016. Eds. Stewardson, C. *et al*. Fisheries Research and Development Corporation: Canberra. http://www.fish.gov.au/

Sawynok, B. (1998). *Fitzroy River: effects of freshwater flows on fish: impact on barramundi recruitment, movement and growth*. Infofish Services National Fishcare Project Report 97/003753, Rockhampton. 59 pp.

Shaklee, J.B., Salini, J. and Garrett, R.N. (1993). Electrophoretic characterization of multiple genetic stocks of barramundi perch in Queensland, Australia. *Transactions of the American Fisheries Society* 122, 685-701.

Sloan, S., Smith, T., Gardner, C., Crosthwaite, K., Triantafillos, L., Jeffriess, B., and Kimber, N. (2014). National guidelines to develop fishery harvest strategies. Final Report for FRDC project number 2010/061. Primary Industries and Regions, South Australia, Adelaide, March. CC BY 3.0. http://frdc.com.au/research/Documents/Final_reports/2010-061-DLD.pdf

Staunton-Smith, J., Robins, J.B., Mayer, D.G., Sellin, M.J. and Halliday, I.A. (2004). Does the quantity and timing of fresh water flowing into a dry tropical estuary affect year-class strength of barramundi (*Lates calcarifer*)? *Marine and Freshwater Research* 55, 787-797.

Sparre, P., Ursin, E. and Venema, S.C. (1989). *Introduction to tropical fish stock assessment, Part 1. FAO Technical Paper 306/1*, Rome. 337 pp.

Stewardson, C. *et al.* (2016). Status of Australian Fish Stocks Reports 2016. http://www.fish.gov.au/

Tanimoto, M., O’Neill, M.F., Robins, J. and Halliday, I. (2009). Seasonal closure and minimum legal size for barramundi in the Gulf of Carpentaria. Technical report prepared for the Gulf of Carpentaria Inshore Fin Fish Fishery review. Department of Employment, Economic Development and Innovation, Brisbane. 26 pp.

Tanimoto, M., Robins, J.B., O'Neill, M.F., Halliday, I.A. and Campbell, A.B. (2012). Quantifying the effects of climate change and water abstraction on a population of barramundi (*Lates calcarifer*), a diadromous estuarine finfish. *Marine and Freshwater Research* 63, 715-726.

Ward, C. (2003). The Gulf of Carpentaria Commercial Fishermen Association Environmental Management Plan. Karumba. 26 pp.

Wesche, S., Lucas, T., Mayer, D.G., Waltishbuhl, D. and Quinn, R. (2013). *Gladstone Harbour fish health investigation 2011-2012.* Department of Agriculture, Fisheries and Forestry, Brisbane. 83 pp.

Webley, J., McInnes, K., Teixeira, D., Lawson, A., and Quinn, R. (2015). *Statewide Recreational Fishing Survey 2012-14*. Department of Agriculture and Fisheries, Brisbane. 145 pp.

Williams, L.E. (2002). *Queensland's Fisheries Resources. Current condition and recent trends 1988-2000.* Queensland Department of Primary Industries, Brisbane. 180 pp.

Appendices

Appendix A – Compilation of management arrangements for Queensland barramundi

Year	Management Measure	Instrument	Source
Unknown	Minimum mesh size 11.5 cm for set-nets inside rivers on the Qld east coast (QEC)		
Unknown	Weekend closure in most rivers and creeks on the (QEC)		Russell (1988)
Unknown	All freshwaters closed to commercial fishing		Russell (1988)
Unknown	Total fishing closure immediately upstream and downstream of coastal fish ladders		
1877	Minimum legal size 16 oz (weight)	***The Qld Fisheries Act of 1877***	Haysom (2001)
1914	Minimum legal size 14" (=35.5 cm)	***The Fish and Oyster Act of 1914 (amended in 1918, 1932, 1935, 1945, 1955)***	Glaister (1990)
1932	Minimum legal size increased to 15" (=38.1 cm)		Glaister (1990)
1955	Minimum legal size increased to 20" (=50.8 cm)		Glaister (1990); QDHM (1959)
1957		***The Fisheries Act of 1957 (amended in 1959, 1962, 1974)***	Haysom (2001)
1976		***The Queensland Fisheries Act of 1976 (amended in 1981, 1982)***	Haysom (2001)
1977	Partial closure of 16 GoC rivers and 6 QEC rivers to commercial net fishing		QFMA (1990); Elmer (1987)
1981	Closed fishing (and take) season 1 November to 1 February (GoC & QEC)	***Barramundi management strategies implemented***	Garrett & Russell (1982)
	Separate limited entry licences (endorsements) for commercial fisheries in the GoC & QEC		Garrett & Russell (1982)
	Minimum mesh size for all set gill nets increased to 150 mm GoC		Garrett & Russell (1982)
	Recreational possession limit of 5 fish per person QEC		Garrett & Russell (1982)
	Protection of barramundi nursery habitats through legislated habitat reserves, fish sanctuaries and fish refuge areas		Garrett & Russell (1982)
	Standardised set-net mesh size at 150 mm (6") north of Cape Flattery on QEC and in the GoC		QFMA (1987)
	Monthly logbook (production return) GOC commercial fishery		

Year	Management Measure	Instrument	Source
1982	Management Plan for Barramundi: restrictions on nets and gears used by commercial fishers; restrictions on how commercial set-nets may be used in rivers and foreshores; reviews of fish habitat areas; limits on size and numbers of commercial vessels used in the fishery	***Queensland Fishing Industry Organisation and Marketing Act 1982***	QFMA (1987)
1988	GOC licence moved from being issued to individuals to being attached to vessels		Ward (2003)
	Introduction of a compulsory daily logbook		
1989	Minimum legal size increased to 55 cm		Russell & Hales (1993)
	Minimum mesh size for set-nets in rivers and creeks increased to 150 mm		DPI (1989)
	Maximum mesh size for set-nets of 245 mm (Max fish size approx. = 1200 mm due to selectivity)		DPI (1989)
	Closures to commercial net fishing: Johnstone River; Plantation Creek; remainder of Burdekin River (delta); remainder of Haughton River; remainder of Proserpine River; Water Park Creek above Kelly's landing; Cawarral Creek; Calliope River upstream of Devil’s Elbow		QFMA (1990)
	Closure to commercial net fishing except bait and general purpose nets: remainder of the Pioneer River		QFMA (1990)
	Closures to all net fishing and the taking of barramundi: Russell/Mulgrave Rivers		QFMA (1990)
	Removal of existing net fishing closures: Barratta Creek; O'Connell River (bait and general purpose nets only)		QFMA (1990)
1990	Prohibition of sale of barramundi under section 35 of the *Fishing Industry Organization & Marketing Act* (i.e., sale of recreationally taken fish in excess to the requirements of the recreational fisher)		QFMA (1990)
1992	Maximum legal size set at 120 cm	***East Coast Barramundi Set (Gill) Net Fishery Management Plan***	QFMA (1990)
	Minimum legal size increased to 58 cm (QEC)		Russell & Hales (1993)
	Introduction of 1 km spawning zones around the mouths of creeks and rivers during the closed season QEC		Cairns Post (1992)

Year	Management Measure	Instrument	Source
1994		***Queensland Fisheries Act 1994***	
1995		***Queensland Fisheries Regulations 1995***	
1996	Minimum set-net mesh sizes (GoC) increased to 162.5 mm (but not more than 245 mm)	***Fisheries (Gulf of Carpentaria Inshore Fin Fish) Management Plan***	Garrett (1997)
	GoC seasonal closure for all inshore net fishing changed from a fixed Nov-Jan inclusive to a variable closure between Oct-Jan inclusive to include the max number of spring and summer full and new moons and night time high tides		Roelofs *et al*. (2003)
1997	Dugong Protection Areas[A] introduced QEC = spatial closures to net fishing		Williams (2002)
	Spatial closures and gear restrictions around the Sweers Island GoC as part of the Gulf Management Plan for dugong protection.		
1999	Separation of the GoC licences to symbols within the GOCIFFF to N3 (<7 nm from coastline –Inshore Gillnet Fishery) and N9 (7 to 25 nm from coastline – Offshore Gillnet Fishery)	***Fisheries (Gulf of Carpentaria Inshore Fin Fish) Management Plan 1999***	
	Minimum legal size increased to 60 cm (GoC)		
	Net attendance requirements legislated		
2008	Revised management arrangements	***Fisheries Regulation 2008***	
2011	Revised management arrangements	***Fisheries (Gulf of Carpentaria Inshore Fin Fish) Management Plan 1999*** repealed***,*** now regulated via ***Fisheries Regulation 2008***	
2012	Minimum legal size decreased to 58 cm (GoC)		Tanimoto *et al*. (2009)
	GoC spawning closure start dates 7 October to 1 February		
2015	Freshwater closures for weirs standardised		
	Net Free Zones introduced November 2015 for Cairns, Mackay and Fitzroy areas, becoming effective in February 2016		

[A] Dugong Protection Areas: Hinchinbrook and Taylor Beach; Cleveland Bay and Bowling Green Bay; Upstart Bay; Edgecumbe Bay; Repulse Bay, Newry Region and Sandy Bay; Ince Bay. Llewewellyn Bay, and Claireview Region; Shoalwater Bay and Port Clinton; Rodds Bay

Appendix B - Collated information on stocked barramundi for each genetic stock in Queensland

Information in the table below is a summary of data collated from: Fisheries Queensland stocking databases (general, SIPS, RFEP and impoundment stocking history) and records compiled by regional fisheries officers (i.e., P. Long, S. Pobar, and M. Pearce). This information (e.g., date, location, number stocked, TL, supplying hatchery and stocking group) was supplemented and corroborated (where possible) between data sources as well as against information available on the internet e.g., newspaper stories and stocking group databases. The numbers in **Table 3** represent the total number of barramundi fingerlings/juveniles released within the spatial extent of a stock (or sub-stock) minus the number of fingerlings/juveniles stocked into impoundments where: (i) fish were unlikely to survive overtopping events and move to downstream reaches, as well as (ii) fish that were likely to have died as a consequence of documented fish kills or large scale cold snap events. 'Year-class stocked' represents the nominal birth date (i.e., 1 January) of released fish.

Table 3 - Numbers of barramundi fingerlings stocked within catchments a genetic region that potentially contributed to the estuarine population

	SGoC	NEC		CEC		Mackay
Year Class stocked	SE sub-stock (16° S to NT border)	Dry Tropics (19° S to 20° S)	Wet Tropics (15° S to 19° S)	Fitzroy	Gladstone	
1986			13,787			
1987						
1988		87,000				
1989		400	10,000			
1990			29,500	1,132		
1991		126,000	21,360			
1992		235,000	2,400	50,000		
1993		98,878	20,398	50,000		
1994		66,650	101,314	40,000		
1995	50,000	62,000	100,206	39,500	200	
1996	292,000	40,463	62,600	36,400	724,894	
1997		161,500	69,743	56,000	135,180	
1998	500	165,020	114,193	8,000	152,450	
1999	70,000	114,246	79,735	86,938	404,704	
2000		60,500	64,393	34,725	131,178	65,000
2001		94,010	53,990	35,600	185,353	157,000
2002		119,976	38,053	20,200	85,716	32,760
2003	12,500	248,275	85,201	62,700	248,362	75,300
2004	25,926	336,000	84,050	44,000	193,396	20,180
2005		68,000	30,397	28,800	149,200	33,688
2006	25,000	115,200	750		117,700	27,033
2007	10,700	109,801	7,000	52,726	207,000	71,005
2008	4,600	58,890	4,245	89,300	176,300	50,334
2009	10,000	58,995		58,092	260,000	24,108
2010	12,000	110,250	20,164	72,375	207,000	37,981
2011	232	17,318		88,730	347,000	40,973
2012	3,232	55,893	2,000	64,400	223,500	15,259
2013	41,000	17,700		16,100	211,075	22,651
2014						1,000
unknown		51,469	10,140			
Total	**557,690**	**2,679,434**	**1,025,619**	**1,653,815**	**4,160,208**	**674,272**

Appendix C - Biological and net selectivity plots

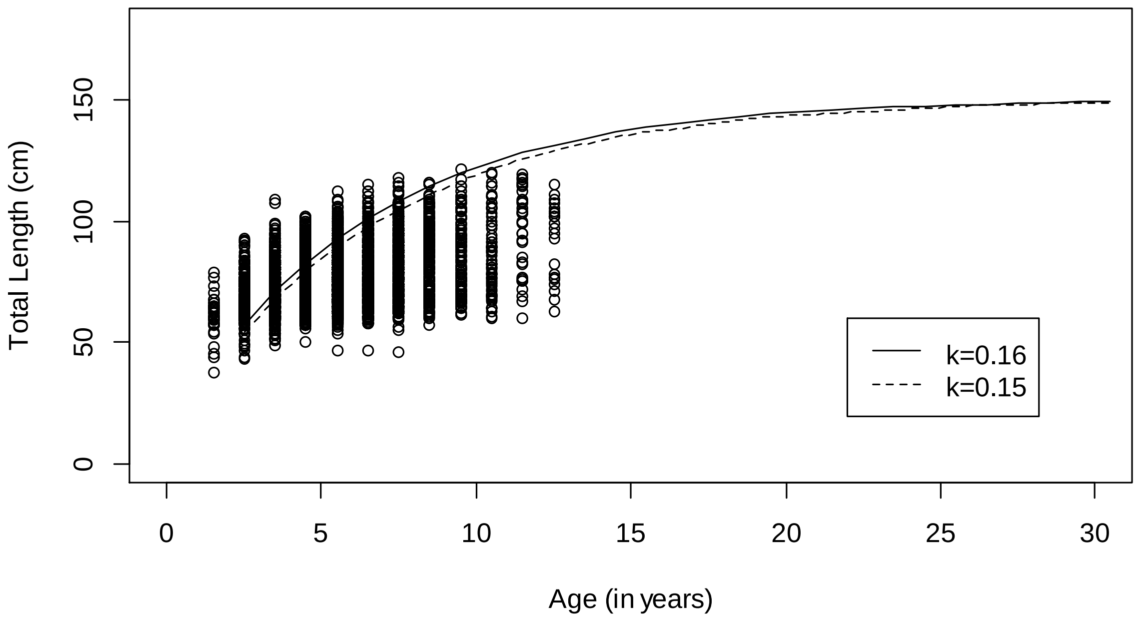


Figure 8 – Length-at-age observed from LTMP data (all years) for Southern Gulf of Carpentaria barramundi, with von Bertalanffy growth curves based on L_{∞} = 150 cm, a_0 = -0.5 and κ = 0.16 (standard) or κ = 0.15 (k low)

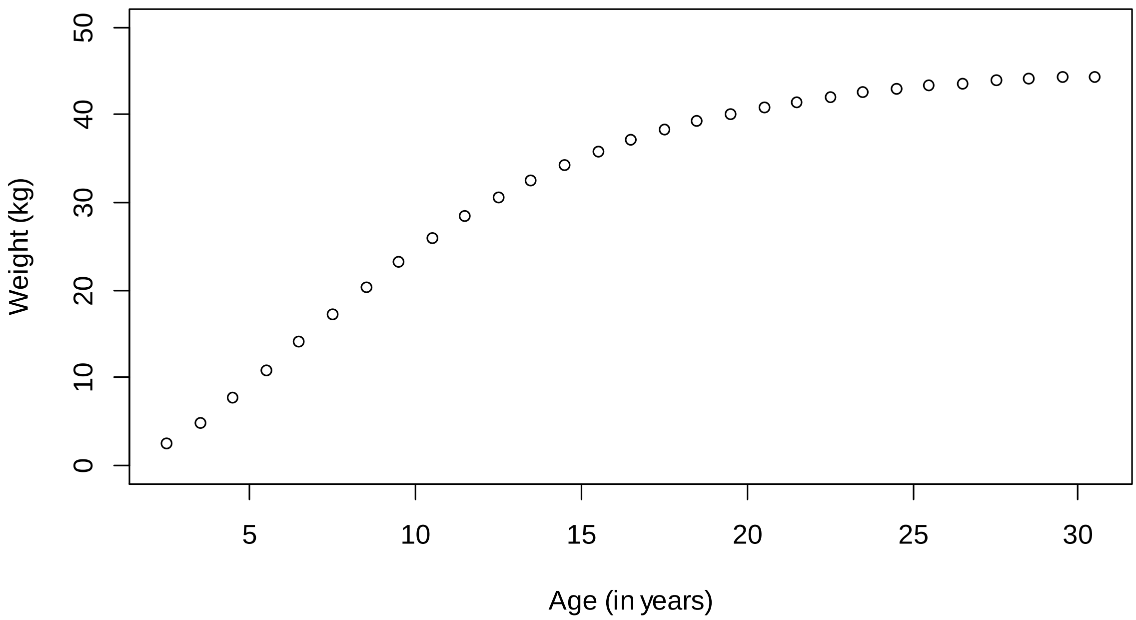


Figure 9 - Weight-at-age for Southern Gulf of Carpentaria barramundi

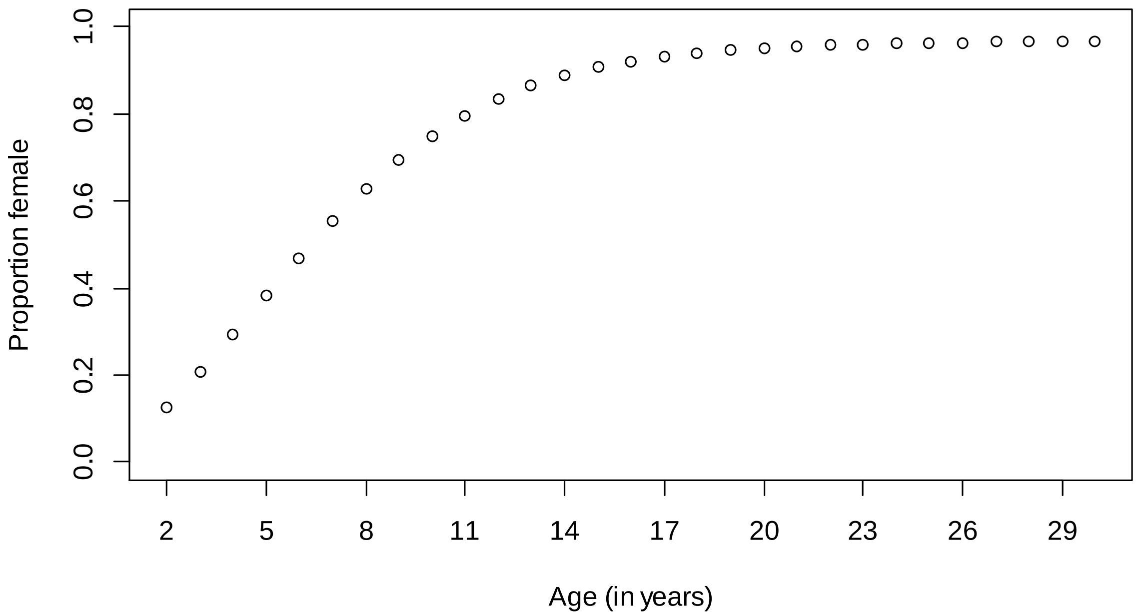


Figure 10 - Proportion female-at-age for Southern Gulf of Carpentaria barramundi

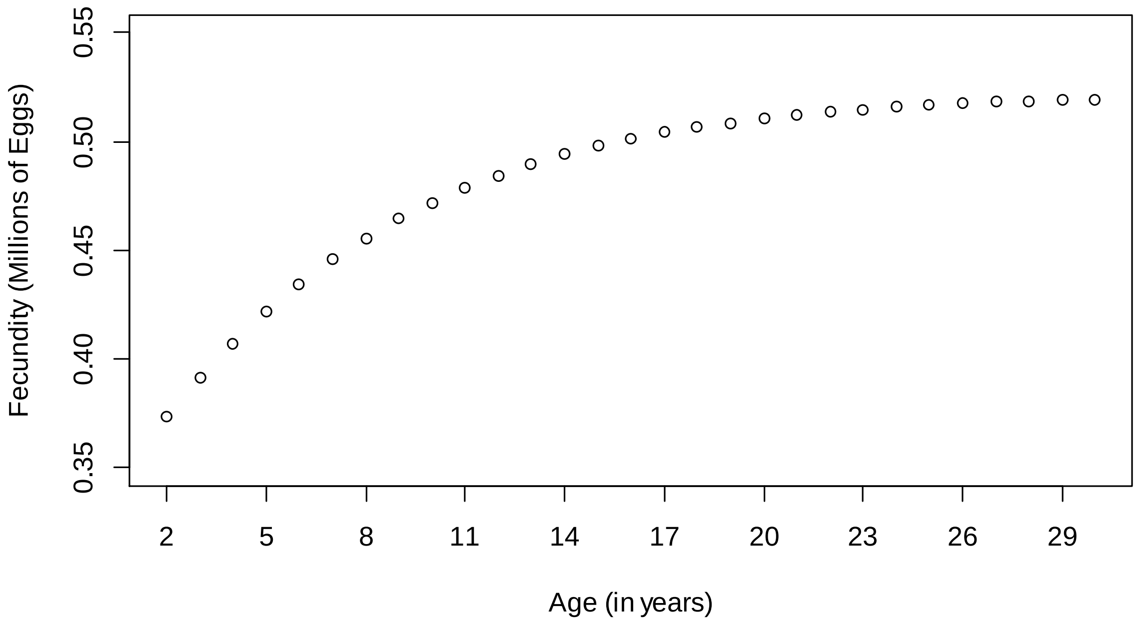


Figure 11 - Fecundity-at-age in millions of eggs for Southern Gulf of Carpentaria barramundi

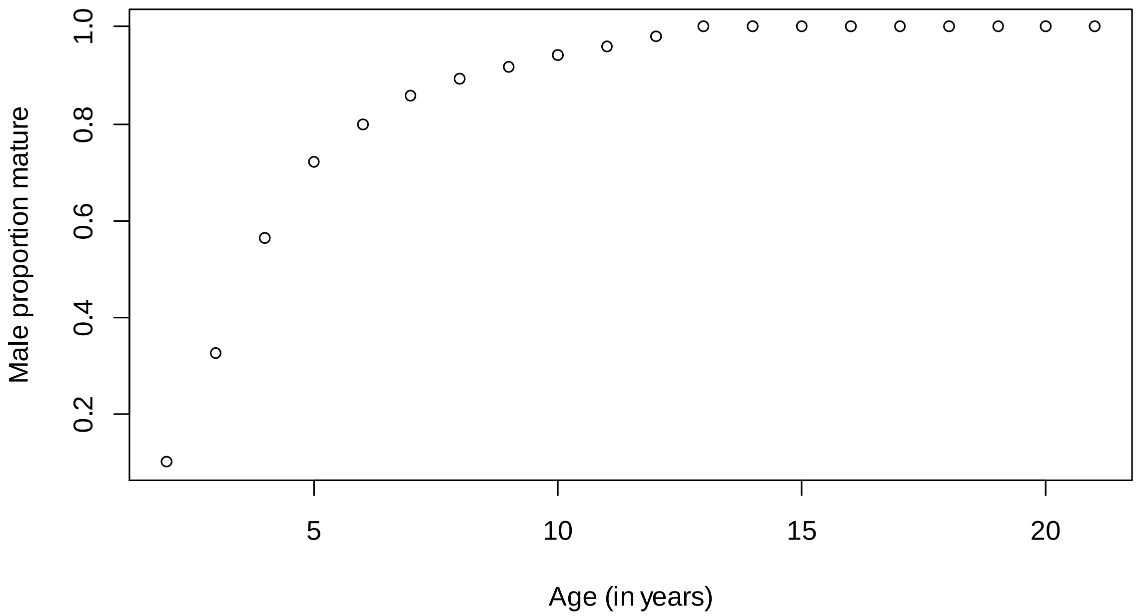


Figure 12 - Proportion male mature for Southern Gulf of Carpentaria barramundi

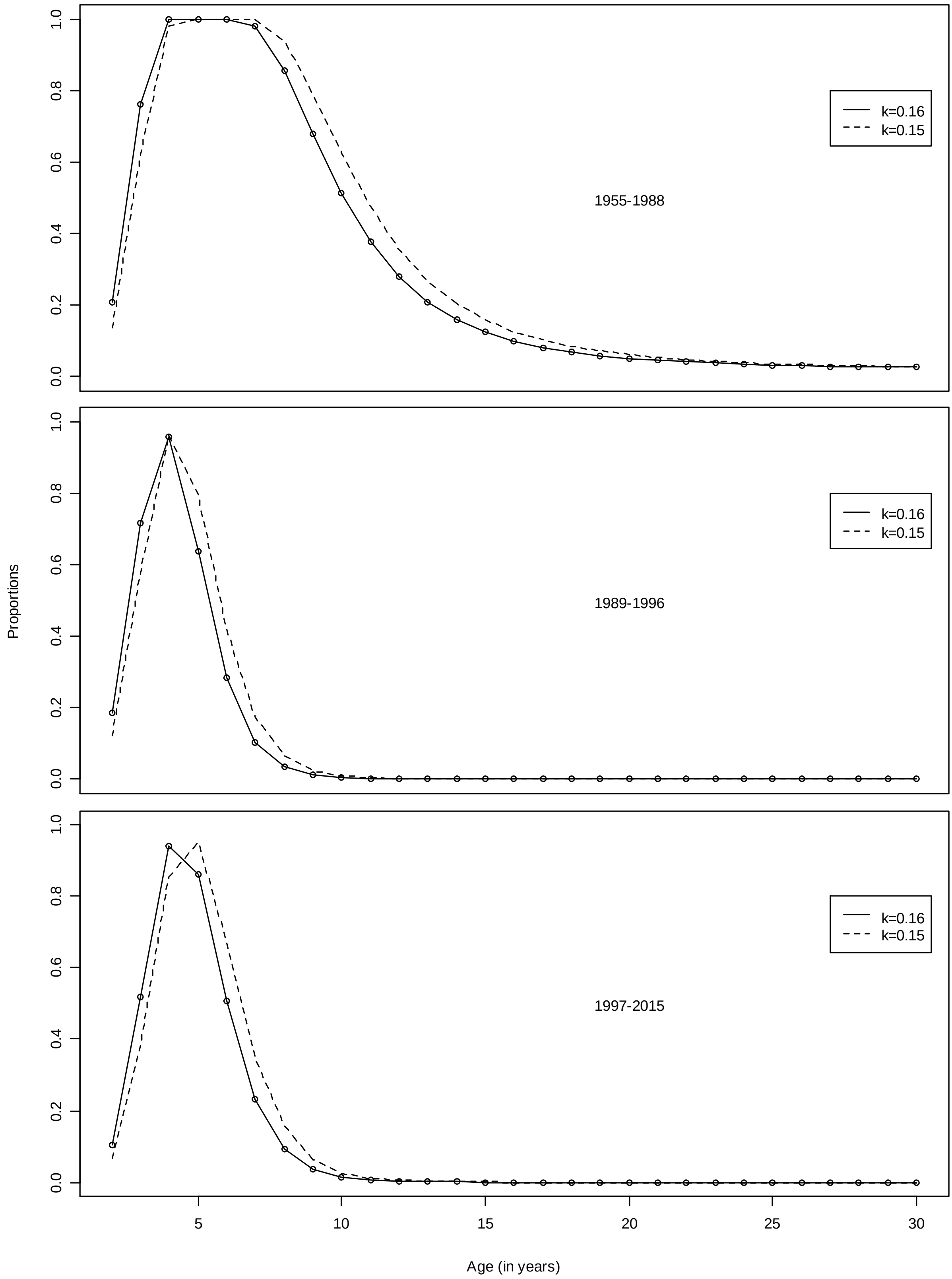


Figure 13 - Selectivity-at-age curves for Southern Gulf of Carpentaria barramundi, where selectivity changes over three periods as a simplification of the complex changes to historical management arrangements and fishing practices, for alternative growth curves where κ = 0.16 (standard) or κ = 0.15 (k low)

Table 4 - Parameter estimates for the five selected scenarios and the remaining 11 scenarios reported in Campbell (2017)

Scenario	h	M	κ	ESW	N_0	$q(t)$	q_{inc}	$l_1(\theta)$	$l_2(\theta)$	$l_3(\theta)$
h=0.8	0.80*	0.26	0.16*	40*	390,700	-12.32	0.088100	-88.5	426.9	516.6
h=0.8, κ low	0.80*	0.33	0.15*	40*	497,920	-12.51	0.150000†	-90.5	426.0	515.8
h=0.9	0.90*	0.21	0.16*	40*	329,580	-10.86	0.008100	-90.5	426.0	514.9
M high	0.92	0.25*	0.16*	40*	325,190	-11.25	0.025000*	-90.4	425.0	517.0
ESW low	0.95	0.20*	0.16*	10*	307,350	-10.42	0.000003	-95.2	423.8	131.5
Base	0.95	0.20*	0.16*	40*	297,770	-10.46	0.000001	-91.0	425.3	514.7
M low	0.98	0.10*	0.16*	40*	185,170	-10.73	0.018200	-91.1	425.9	512.4
ESW high	0.95	0.20*	0.16*	100*	288,710	-10.56	0.000000†	-84.4	429.0	1271.0
κ low	0.96	0.20*	0.15*	40*	283,150	-10.85	0.025000	-90.9	426.8	513.5
Catch fit all	1.00†	0.25*	0.15*	100*	265,380	-12.51	0.150000†	-78.8	748.2	1265.5
h=0.7	0.70*	0.31	0.16*	40*	537,510	-13.11	0.150000†	-86.7	427.6	518.0
h=0.6	0.60*	0.35	0.16*	40*	835,470	-13.60	0.150000†	-84.8	428.3	519.2
h=0.5	0.50*	0.39	0.16*	40*	1,980,400	-14.56	0.150000†	-83.2	428.9	520.1
Base, ALK	0.90	0.20*	0.16*	40*	313,630	-10.64	0.000000†	-90.6	425.6	514.1
ESW low, ALK	0.90	0.20*	0.16*	10*	330,140	-10.55	0.000000†	-95.5	424.3	131.5
h=0.8, ALK	0.80*	0.26	0.16*	40*	455,570	-10.95	0.000100	-89.6	425.6	514.3

* indicated fixed value; † indicates parameter estimate hit upper or lower bound

Table 5 - Model outputs for the five selected scenarios and the remaining 11 scenarios reported in Campbell (2017)

Scenario	Egg Production Ratio (EPR)			Maximum Sustainable Yield (MSY) (tonnes)			Egg Production Ratio at MSY (EPR_{MSY})			Fishing Mortality at MSY (FR)		
	20^{th}	50^{th}	80^{th}	20^{th}	50^{th}	80^{th}	20^{th}	50^{th}	80^{th}	20^{th}	50^{th}	80^{th}
h=0.8	0.36	0.47	0.60	540	582	633	1.66	2.16	2.76	0.42	0.50	0.57
h=0.8, k low	0.28	0.40	0.54	569	610	661	1.23	1.75	2.37	0.48	0.59	0.70
h=0.9	0.22	0.31	0.41	546	595	643	1.38	1.91	2.49	0.42	0.50	0.59
M high	0.36	0.45	0.55	583	618	654	2.10	2.75	3.63	0.34	0.41	0.47
ESW low	0.21	0.29	0.37	571	609	654	1.42	2.05	2.71	0.40	0.48	0.57
Base	0.29	0.37	0.45	595	634	678	1.99	2.58	3.26	0.34	0.39	0.44
M low	0.13	0.17	0.21	513	544	588	1.08	1.44	1.92	0.51	0.59	0.67
ESW high	0.38	0.46	0.54	602	637	678	2.53	3.98	3.98	0.29	0.36	0.36
κ low	0.15	0.21	0.27	568	608	662	1.03	1.47	1.96	0.51	0.59	0.67
Catch fit all	0.46	0.53	0.61	502	531	558	3.5	4.07	4.72	0.32	0.36	0.40
h=0.7	0.52	0.66	0.83	537	579	631	1.95	2.78	3.12	0.40	0.47	0.55
h=0.6	0.74	0.93	1.16	515	578	692	2.33	2.96	3.66	0.34	0.44	0.53
h=0.5	1.31	1.65	1.91	707	1457	2507	3.64	4.52	5.27	0.08	0.14	0.32
Base, ALK	0.27	0.36	0.48	602	639	682	1.46	2.08	3.03	0.36	0.45	0.52
ESW low, ALK	0.2	0.31	0.42	611	656	708	1.19	1.78	2.58	0.39	0.31	0.56
h=0.8, ALK	0.45	0.79	1.17	584	725	1328	2.06	3.59	5.22	0.14	0.31	0.51